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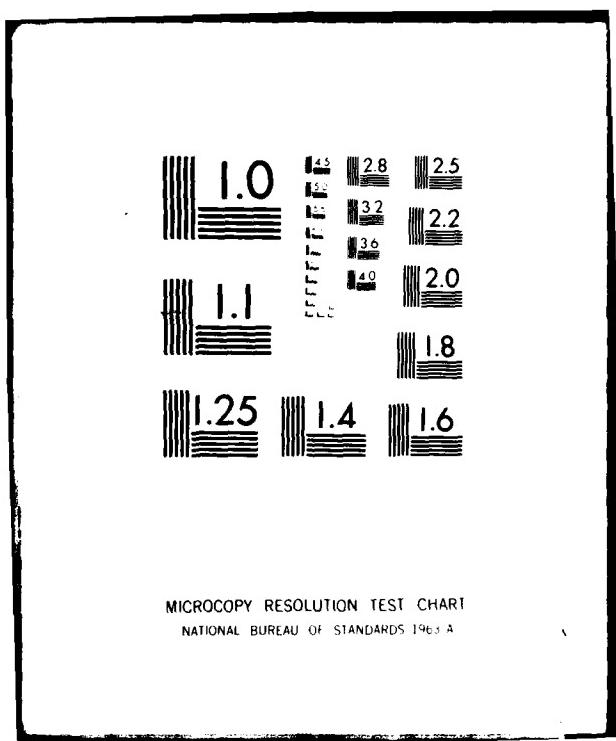
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March 1980

DENSIFIED BIOMASS AS AN ALTERNATIVE ARMY HEATING AND POWER PLANT FUEL

by
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This investigation evaluated the technical and economic potential of using densified biomass (principally wood pellets) as a coal substitute in Army heating and power plants. The report reviews Department of Defense (DOD) experience with and tests of wood pellets; production of wood pellets (excluding silvicultural aspects); handling, storing, and feeding; combustion; major environmental considerations; and economics of use.

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It is concluded that wood pellets appear to be a viable alternative to coal in stoker-fired Army heating and power plants, but that their use will entail some loss of boiler fuel-to-product conversion efficiency and some sacrifice of boiler maximum continuous rating.

The report recommends using wood pellets wherever technically and economically feasible, establishing standard technical specifications to aid in wood pellet procurement, and monitoring installation-scale wood pellet systems continuously both to validate the wood pellet concept over long-term use and to identify technological gaps and opportunities associated with wood pellet use.

The report contains an analysis of wood pellets' characteristics and ability to flow, and a design for a 250-ton (225-MT) bin and feeder system.

FOREWORD

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DENSIFIED BIOMASS AS AN ALTERNATIVE ARMY HEATING AND POWER PLANT FUEL

1 INTRODUCTION

Background

Using biomass as an alternate fuel could be a practical method for reducing fossil fuel consumption at Army heating and power plants.* Of all forms of biomass currently and potentially available to Army installations as an energy resource, wood has the greatest promise for widespread use over the foreseeable future. The Army manages approximately 1,500,000 acres (607 050 hectares) of forest and annually sells 75,000,000 board feet (83 705 MT) of sawtimber and 85,000,000 cords (94 562 500 MT) of pulpwood to contractors working those lands.[1] Comparable quantities of unmarketable timber may be left to waste[2] Other sources of wood on Army installations include construction and demolition waste, packaging, carpentry shop scrap, and waste from demilitarization activities. In addition, the amount of commercially available wood waste and processed wood fuel is on the rise near many installations.

Current interest in using biomass as an alternate fuel is stimulated by the vast reductions in fuel oil and natural gas consumption called for by the Army's Energy Plan.[3] Coal is now gaining preference as a primary fuel in both new and converted Army heating and power plants. The Army coal conversion effort probably will emphasize proven stoker-firing technologies, since nearly all installations have neither the technical need for, nor the economy of scale to support, large pulverized coal-firing systems.[4] The average Army central power plant has less than 200 MBtuh (59 MWt) capacity, consists of multiple boilers rated approximately 40 MBtuh (12 MWt), and produces 150 psi (1034 kPa) saturated steam for heating and cooling.[5]

In most cases, use of biomass may proceed simultaneously with an installations efforts to move away from fuel oil and natural gas as primary heating and power plant fuels. However, to be used effectively as either a supplement to or substitute for stoker-fired coal, raw or virgin biomass must be processed into a form and quality suitable for use across the entire spectrum of an installation's coal system unit operations — with little or no capital modifications to those operations. For stoker-firing applications, the material's moisture content must be reduced (often from up to 50 percent to 10 percent by weight), and its energy density increased. Proven and simple operations of drying and pelleting may produce for Army heating and power plants an alternate fuel which is more environmentally compatible and cost effective than coal.

Objective

The objective of this investigation was to evaluate the technical and economic aspects of producing and using densified (or pelleted) wood as an alternate fuel in Army heating and power plants.

Approach

This investigation was conducted according to the following steps:

1. A systematic review of tests and experiments with densified biomass on Department of Defense

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*Definitions used in this report follow those under the American National Standard American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. Accordingly, a power boiler is one in which steam or other vapor is generated at a pressure of more than 15 psi (103 kPa), and a heating boiler is one in which steam is generated at pressures not exceeding this quantity; heating and supply hot water is generated up to 160 psi (1103 kPa) and boiler outlet temperatures are not greater than 250°F (121°C); potable hot water is generated in lined heaters at temperatures not greater than 210°F (99°C) and 160 psi (1103 kPa). ASME defines high-temperature hot water as being generated at pressures greater than 160 psi (1103 kPa) and temperatures greater than 205°F (121°C). As used in this investigation, the term "biomass" does not include mixed solid waste, but can refer to individual constituents of a solid waste stream, such as paper, whose origins are photosynthetic. To facilitate comparative fuel analyses, biomass here is treated as a combustible fuel.

[1] Facilities Engineering Summary of Operations, FY77 (Department of the Army [DA], Office of the Chief of Engineers, DAEN-MPO-R, 1978).

[2] M. Hiser, ed. Wood Energy (Ann Arbor Science, 1978).

[3] Army Energy Plan, ADA 057 987 (Headquarters, DA, 1978).

[4] S. A. Hathaway, M. Tseng, and J. S. Lin, Project Development Guidelines for Converting Army Installations to Coal Use, Interim Report E-148/ADA068025 (U.S. Army Construction Engineering Research Laboratory [CERL], March 1979); Stokers for Industrial Boilers – Assessment of Technical, Economic, and Environmental Factors, PB288689 (Battelle Columbus Laboratories, 1975).

[5] Personal Communication with Mr. R. D. Winn and Mr. J. Donnelley, Directorate of Military Programs, Office, Chief of Engineers (OCE), Washington, DC, 13 June 1979.

(DOD) installations was conducted, and experience pertaining to storage, handling, feeding, combustion, environmental impact, energy efficiency, and economics evaluated.

2. Published literature on producing and using densified biomass in installation-scale systems was reviewed.

3. Extensive discussions (particularly emphasizing fuel production) were held with manufacturers, vendors, and operating personnel of densified biomass systems).

4. To complement data and information obtained through the test review, field tests of densified biomass were conducted at two Army installations representing small heating and large power plants: Forts McCoy and Benjamin Harrison, respectively.

5. Support was provided at Fort McCoy to retrofit a small Army heating plant to fire green wood chips; this test provided baseline data for later evaluating the performance of dry, processed pellets.

6. A contract for laboratory analysis of processed wood pellets and design of a storage and feeding system for a typical installation application was issued.

7. A structured evaluation was made of data and information gathered in the above steps, and this report, which contains major findings, recommendations, and conclusions from the investigation, was prepared.

2 DOD TESTS USING DENSIFIED BIOMASS

General

Four densified biomass tests have been conducted to date within DOD. With one exception, all tests have been short-term experiments and have been largely successful in illuminating the potential of densified biomass as an alternate fuel in coal-designed systems. By far the longest experience with this material has been at Kingsley AFB, OR, where biomass has been substituted for coal since late winter of 1978. The experience of industries and utilities with densified biomass has been mostly of a short-term experimental or demonstration nature; information from this sector is used in the following discussion of DOD tests when appropriate.

Kingsley AFB, OR[a]

Pelleted processed wood marketed under the trade name "Woodex" has replaced coal in two boilers at Kingsley since February, 1978. The boilers are identical Keeler package watertube units equipped with shaking grates and Riley frontwall mechanical spreader stokers. Each boiler is designed to raise 12,000 lbh (5443 kg/hr) 100 psi (689 kPa) saturated steam for heating and cooling. Steam load per boiler averages 10,000 lbh (4396 kg/hr), and the average hourly steam load supported by Woodex during the burn period is 20,000 lbh (9072 kg/hr).

Woodex is produced in Brownsville, OR, by the Bio-Solar Corporation and shipped approximately 200 miles (320 km) by rail to Kingsley AFB. The fuel is produced from hogged wood and unmarketable timber (mostly pine) by shredding, drying, pelleting, and screening. The pellets average 0.13 in. (3.18 mm) in diameter by 0.75 in. (19.05 mm) in length. Proximate and ultimate analyses of the Woodex are not available from the user. Air Force personnel estimate the heating value of the Woodex to be 8360 Btu/lb (19 440 kJ/kg) on an as-fired basis, its ash content to be on the order of 2 percent by weight, its moisture content to be approximately 13 percent by weight, and its loose bulk density to be 34 lb/cu ft (544 kg/m³). This is in contrast to coal normally used at the plant, which has an as-fired heating value ranging between 11,000 and 12,000 Btu/lb (22 579 to 27 904 kJ/kg), up to 10 percent ash, up to 8 percent moisture, and a loose bulk density on the order of 50 lb/cu ft (801 kg/m³). Throughout the test period, about 1.35 times as much Woodex by mass is required to do the work of 1 unit of coal.

Minor problems have been experienced with handling and storing Woodex at Kingsley AFB. When the installation began using Woodex, a chip blower was installed for unloading the material, and a 4-in. (102-mm) flexible duct was installed from pellet storage to the coal chute cleanout hatch. The coal supply was cut off by closing the coal silo entrance to the coal chute. Early on, there was a tendency for minor bridging of the Woodex in the coal chutes. Attempts to restore flow by using a water jet resulted in pellets swelling and offering more resistance to free flow. Mechanical flow aids are now employed when necessary. According to Air Force personnel, there have

been no major problems with open storage of Woodex, even when the material is exposed to rainfall over short periods. Personnel have observed some breakdown of Woodex due to handling, but have considered this a trivial concern.

According to Air Force personnel, furnace and boiler performance has been satisfactory when firing Woodex as a complete substitute for coal during typical steam loads of 83 percent. Each of the two boilers firing Woodex consumes about 12 tons/day (10.8 MT/day) fuel, and, although 35 to 40 percent more Woodex than coal on a mass basis must be fired for equal furnace heat release, there has been no difficulty in increasing the feed rate to achieve this. The major operational changes made to accommodate Woodex firing were to reduce combustion air by one-third, reduce induced draft by two-thirds, increase the stoker speed and discharge feed angle, and increase the fuel feed rate. Throughout the burn period, an ash bed depth of 1 in. (25.4 mm) is maintained over the shaking grates to protect grate material from thermal stress due to radiant heat. Minor problems have been experienced with underfire air velocities occasionally being too high, resulting in partial fluidization of the fuel bed and entrainment of fines into the combustion gases, and with fines in the fuel—fines which readily entrain when mechanically fed to the furnace.

When a blend of Woodex and coal is fired, however, significant slagging occurs, along with sometimes severe clinker formation, because of the difference in the burning temperatures between Woodex and coal. Accordingly, personnel recommend against firing a fuel mixture.

Although fugitive dust is a problem when using Woodex, Air Force personnel are optimistic that the environmental impact of using Woodex will be less than that of coal. Noticeable dust emissions occur as Woodex is delivered to a receiving pit before being moved to the silo. Delivery of the fuel from the silo to the boiler is essentially an enclosed operation and does not produce a dust problem. Plant personnel feel that use of Woodex has resulted in an improved working environment because wood fines are less toxic and generally cleaner than coal dust.

Kingsley AFB implemented Woodex largely to comply with U.S. Environmental Protection Agency (USEPA) emission requirements. Since Woodex contains only a negligible amount of sulphur, its use results in essentially no emission of sulphur oxides.

A baghouse, originally installed for particulate removal when coal was fired, is bypassed when Woodex is used. Although never tested, particulate emissions from Woodex are apparently compliant, as evidenced by a clear smoke plume.

Use of Woodex as a coal substitute at Kingsley AFB has been economically advantageous. The fuel is purchased at a delivered cost of $36.50/ton ($40.24/MT), which includes $12.50/ton ($13.78/MT) shipping. The delivered cost of coal is $48.00/ton ($53.92/MT). On an energy-unit basis, the delivered cost of Woodex is $2.17/MBtu ($2.07/kJ), while that of coal is $2.18/MBtu ($2.06/kJ). Cost of Woodex f.o.b. from the site of production is $1.43/MBtu ($1.36/kJ). Although the delivered costs of Woodex and coal are essentially the same on an energy-unit basis, Woodex has, at Kingsley AFB, the additional economic advantages of reduced boiler maintenance and repair, reduced fly ash handling, reduced ash removal, and the avoided cost of air pollution control system operation. According to Air Force personnel, boiler cleaning is easier and its frequency reduced ninefold (from three times per shift to once daily). When firing coal, the ash silo had to be discharged once weekly, but when using Woodex, this task is performed once every 4 to 6 weeks because of reduced fuel ash content. In addition, plant personnel estimate a savings of at least 800 man-hours per year in baghouse maintenance and of an undetermined but large amount of costly electrical power in baghouse operation. Although these savings have not been quantified, it is clear that Woodex can have a distinct economic advantage over coal. This advantage could grow significantly if the avoided costs of installing, operating and maintaining a flue gas desulphurization system are considered.

Fort McCoy, WI

Woodex replaced coal in several small heating plants at Fort McCoy, WI, during tests conducted in March 1978, and excess test pellets were used in one heating plant as a coal substitute for several months thereafter. The boilers tested were small in contrast to the large central installation power systems at which other tests and demonstrations were conducted. The heating plants were rated from 0.25 to about 2.0 MBtuh (0.07 to 0.59 MWt), individually supplying heating steam to barracks, maintenance facilities, shops, and administrative activities. The units tested were firetube boilers equipped with an auger-feed, underfeed retort stoker in a rectangular, refractory-faced combustion chamber.

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The Woodex tested was produced by Tennessee Woodex, Inc., Knoxville, TN, and shipped in covered dump trucks to Fort McCoy. The fuel was manufactured largely from hogged pine and pine bark by shredding, drying, and pelleting. A final screening stage to remove fines from the Woodex product was not in operation at the time of manufacture. Proximate and ultimate analyses of the Woodex were not available, but Army personnel estimated the heating value of the Woodex to be 8250 Btu/lb (19 185 kJ/kg) on an as-fired basis, its ash content to be on the order of 2 percent by weight, its moisture content to be approximately 12 percent by weight, and its loose bulk density to be 38 lb/cu ft (608 kg/m³). Coal normally used at Fort McCoy has an as-fired heating value of about 11,000 Btu/lb (22 579 kJ/kg), up to 12 percent ash, up to 7 percent moisture, and a loose bulk density on the order of 50 lb/cu ft (801 kg/m³). During the tests, it was observed that from 35 to 40 percent more Woodex than coal (by mass) was required to do a similar amount of work.

Virtually no problems were encountered in handling and storing the Woodex at Fort McCoy. Forty tons of fuel was delivered by truck to a vacant hangar building where it was stored on a dry, well-drained concrete floor in piles no greater than 5 ft (1.52 m) high. Minor dusting was observed during dumping. The fuel was loaded by front-end loader into conveyor-equipped coal trucks which delivered it to enclosed, dry bins adjacent to the heating plants in which it was tested. As the fuel was conveyed from the trucks into the bins, there was some spillage and dusting from the conveyors. Both difficulties, however, were relatively minor and presented no more of a housekeeping problem than coal. Once in the bins, the Woodex was moved by bucket or shovel to the floor-level boiler feed hoppers, which held about 1.5 cu yd (1.15 m³) of material. Plant personnel favored Woodex over coal during in-plant handling because of the pellets' relative cleanliness. No bridging problems occurred as the Woodex flowed down the feed hopper to the enclosed constant flight and pitch auger which fed the stoker, nor were there any observable problems with auger performance when moving the fuel to the stoker.

Combustion of Woodex in the heating plants evaluated was generally satisfactory. Each boiler was examined for its capability to fire Woodex as a coal substitute at full load and at normal turndown ratios. In addition, a small number of tests were conducted during which blends of Woodex and coal were fired. Since all tests were conducted to determine whether any immediately observable problems would be en-

countered when firing Woodex during normal boiler operation, no instrumentation and monitoring equipment was used other than what was in-place in the plants. When Woodex was substituted for coal, the heating plants were able to sustain full load operation and adequate response to fluctuations in steam demand over the short term. Stack gas content of CO ranged from 4 percent to 8 percent, that of CO_2 ranged from 11 percent to 16 percent, and temperatures ranged between 600°F (316°C) and 650°F (343°C) (approximately 150°F [66°C] higher than when firing coal). Relatively large flame travel was observed when firing Woodex, but there was no apparent problem of impingement or carryover to the firetube section. It was felt that combustion could be improved by elevating the backwall overfire air nozzles and by providing finer control over overfire and underfire air. When blends of Woodex and coal were fired, combustion and boiler performance again was satisfactory over the short term; however, the fuel bed displayed a strong tendency to clinker, and generation of smoke increased. As discussed later, this was attributed to the technical inability to optimize combustion air.

Portable smoke detectors inserted into the ductwork between the boiler and stack indicated a Ringelmann value averaging about 2 when Woodex was fired and a value of about 3 when blends of Woodex and coal were fired. Reduced particulate emissions coupled with relaxation of state emission regulations from 0.15 lb/MBtu (64 ng/J) to 0.6 lb/MBtu (258 ng/J) could mean that Fort McCoy's heating plants can operate in compliance with emissions standards when firing Woodex as a substitute fuel.[7] But this must be verified by thorough stack testing during the heating season when the plants generally operate at or near full load.

Use of Woodex as a coal substitute at Fort McCoy clearly has potential economic advantages if a nearby supply of the fuel can be found. The fuel tested was purchased from Tennessee Woodex, Inc., at a truck-delivered cost of $90.00/ton ($98.90/MT), which included $62.00/ton ($68.13/MT) shipping. The delivered cost of coal to Fort McCoy is now $40.00/ton ($43.96/MT) and is expected by installation personnel to rise to $48.00/ton ($52.75/MT). On an energy-unit basis, the delivered cost of 8400 Btu/lb (19.5 mJ/kg) Woodex was $5.36/MBtu ($5.08/kJ), while the anticipated

Personal communication with Mr. R. Dodds, Air Management Section, Wisconsin Department of Natural Resources (Madison) and Mr. S. Hathaway (CERL), 9 August 1979.
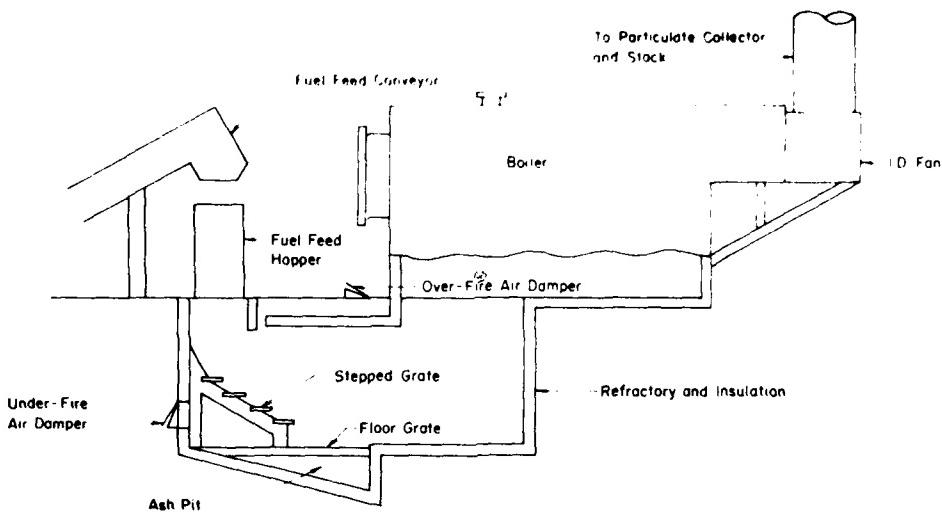
Figure 1. Conifer Burner™ of type being implemented at Fort McCoy, WI.

cost of 11,500 Btu/lb (26.7 mJ/kg) coal is $2.09/MBtu ($1.99/kJ), or less than half the cost of Woodex. However, the as-manufactured cost of Woodex was $1.43/MBtu ($1.36/kJ), or about 27 percent of its delivered cost and 68 percent of the projected cost of coal. A reliable supply of Woodex nearer the installation could easily reduce transportation costs and thereby make Woodex a clear economic competitor with coal for long-term use.

As an adjunct to the Woodex tests, Fort McCoy is in the process of modifying a heating plant to fire locally available green wood chips as a substitute for coal. A Conifer Burner™ was recently received and is being retrofitted to a small boiler serving an auto-motive maintenance facility (Figure 1). When this unit begins operating, it will provide techno-economic data which the Army will use to determine the relative merits of using either pelleted wood fuel or chips as a heating and power plant fuel substitute for coal. The retrofit is being made at a cost of $3500, and 5000 Btu/lb (11.6 mJ/kg) wood chips are available for approximately $7.00/ton ($7.69/MT) or $1.43/MBtu ($1.36/kJ), equivalent to the price the installation expects to pay for coal in the near future.

Rock Island Arsenal, IL

Approximately 148 tons (134 MT) of Woodex manufactured by Bio-Solar of Brownsville, OR, was tested as a coal supplement and substitute on 9 and 10 April 1979.[*] The tests were run in a Wicks watertube boiler

*Personal communication with Mr. D. Mueller, Facilities Engineering Office, Rock Island Arsenal, IL, 26 April 1979.

equipped with Hoffman mechanical spreader stokers and a traveling grate. The unit was rated at 75,000 lb/hr (34 019 kg/hr), 150 psig (1034 kPa) steam generating capacity, and was equipped with Joy mechanical collectors and Hays boiler controls. The Woodex tested was produced from bark and other wood products by the process described earlier in the discussion of the Kingsley AFB test (p. 10). Woodex pellets measured 0.25 in. (6.4 mm) diameter by 0.50 in. (12.7 mm) length, and had an as-fired heating value of 8100 Btu/lb (18 836 kJ/kg) and a bulk density of 34 lb/cu ft (544 kg/m³).

Experience with passing Woodex through the coal handling and storage system was generally satisfactory and no modifications were made to in-place coal equipment for the test. The fuel was delivered directly to the boiler plant in enclosed, bottom-dumping rail cars and discharged to a receiving pit. From there it was taken by vibrating conveyor to the bucket elevator, which carried it to the bunker where it was distributed by belt conveyor. It was removed from the bunker by a weigh larry and loaded into the boiler frontwall feed hopper. A considerable amount of dust was generated during all fuel handling operations, par-ticularly where there were long drops—in the elevator pit and bunker area, for example. Representative dust concentrations were measured and analyzed by Arsenal Safety and Industrial Hygiene personnel, who determined that concentrations were below those necessary for an explosive atmosphere, but nonetheless could present a health hazard. A light water mist applied to the fuel during handling operations lowered

dust levels without noticeable degradation of the fuel. For continued use of Woodex or similar fuels, arsenal personnel recommend that measures be taken to reduce dusting from fuel handling equipment, breathing and eye protection devices be used, and substantial accumulations of dust not be allowed on floors and equipment.

The Woodex tests at Rock Island Arsenal indicated that the boiler generally performed well when firing the material. The boiler was cold-started and manually brought up to partial capacity on Woodex. Minor adjustments were made to change fuel feed trajectory and feed rate. Underfire air was reduced considerably from that normally used for coal, and overfire air was maintained to ensure complete combustion. Grate speed was reduced in order to maintain a sufficient ash bed to protect grate materials from furnace radiant heat. Throughout the tests, boiler operation was maintained on manual control because the automatic controls could not accommodate the low air flows required by Woodex. The tests indicated that over the short term the boiler could be fired with Woodex at 0.7 to 0.8 capacity, without serious problems, on manual operation, and with achievable operational and control changes.

Three USEPA Method 5 particulate emissions tests conducted during the Woodex experiment indicated that emissions when firing Woodex were below those when firing Illinois bituminous coal, but still did not comply with State of Illinois particulate emissions limitations. Allowable particulate emissions for the level of boiler operation at which Woodex was tested are approximately 18 lb/hr (8.2 kg/hr). The three particulate emissions tests showed Woodex emissions to be approximately 44, 31, and 26 lb/hr (20, 14, and 12 kg/hr, respectively), as boiler controls were progressively adjusted to optimize Woodex performance. Arsenal personnel observed only very light smoke from the stack during the first test, and a clear plume for the ensuing two. Particulate emissions when firing coal have been as high as 65 lb/hr (29.5 kg/hr) at comparable boiler loads.

The Woodex experiments at Rock Island Arsenal indicated that pelleted wood fuel may not compete economically with coal even if a local supply of the alternate fuel were available. Illinois bituminous coal with an as-fired heating value of 10,500 Btu/lb (22 413 kJ/kg) is used at the Arsenal with a delivered cost of $29.00/ton ($32.22/MT), or $1.38/MBtu ($1.31/kJ). Woodex with a heating value of 8100 Btu/lb (18.8 mJ/kg) was purchased at a delivered cost of $90.00/ton ($100.00/MT) or $5.56/MBtu ($5.28/kJ). Its cost f.o.b. Brownsville, OR, was $28.00/ton ($31.11/MT) or $1.73/MBtu ($1.65/kJ). Accordingly Woodex cannot immediately compete with coal at the Arsenal; a locally available supply might be competitive, however, if the delivered price of coal were to rise to about $36.40/ton ($40.44/MT). Of course, this cost comparison considers only the fuel and transportation costs and assumes that the conditions of using Woodex and coal are equal. As illustrated in the chapter on economics, this is in fact not the case. Since the future costs of flue gas desulphurization are avoided by using pelleted wood in favor of coal, the alternate fuel can be economically preferable over the long term.

Fort Benjamin Harrison, IN

Two tests using Woodex from Tennessee Woodex, Inc., Knoxville, were conducted at Fort Benjamin Harrison in March and April 1979. The Woodex used was similar to that tested at Fort McCoy. Approximately 40 tons (36 MT) were fired during each test period. These tests—the most comprehensively instrumented to date—confirmed experiences elsewhere in DOD with pelleted wood fuel, and determined more precisely than other tests the limitations of the alternate fuel both as a substitute for and a supplement to coal. The first test was conducted as a pretest to determine if any severe problems would occur when using Woodex in a central power system designed for coal. The success of the pretest paved the way for the more intensive second experiment.

The boiler tested was one of four nearly identical units in Central Heating Plant No. 1 and is shown in Figure 2. It is a 1952 Wickes two-drum, watertube boiler designed to fire 12,700-Btu (13 396-J), 1.9-percent sulphur, 12-percent ash bituminous coal screened to 15 percent minus 0.25 in. (6.4 mm) from the Central Utility Strip Mine in Montgomery, IN. The design's maximum steam-generating capacity is 32,000 lb/hr (14 515 kg/hr). The waterwall heating surface is 485 sq ft (45.1 m²) with 3-in. (76.2-mm) side tubes spaced on 7.5-in. (152.4-mm) centers. Boiler heating surface is 4713 sq ft (438 m²) with 2-in. (51-mm) side tubes spaced on 5-in. (127-mm) centers. Overall depth is 17 ft (5.2 m) with 11 ft, 8 in. (3.6 m) from front to mud drum center. Tile-to-tile width is 11 ft (3.4 m), and height from floor to steam outlet is 19 ft, 8 in. (6 m). The upper drum is of the suspended type and measures 54 in. (1.4 m) inside diameter (i.d.) by 12 ft., 3.5 in. (3.8 m) long. The mud drum measures 37 in. (0.9 m)
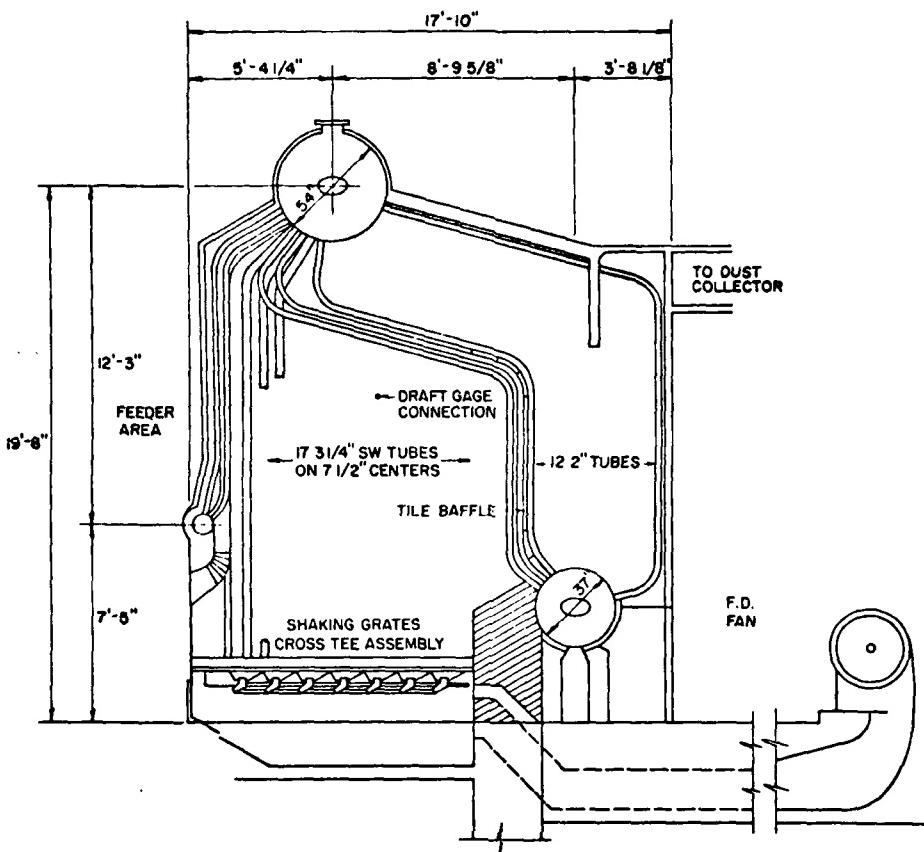
Figure 2. Boiler tested at Fort Benjamin Harrison, IN.

i.d. by about 10 ft (3 m) long. Normal operating pressure is 100 psig (690 kPa), with a maximum of approximately 160 psig (1103 kPa). Under normal operating conditions, feedwater temperature is 225°F (107°C) and steam temperature about 350°F (177°C). The boiler is equipped with Westinghouse starters, Hays-Republic pneumatic controls, dual steam pulse sootblowers, and both undergrate and overfire air. The unit can be operated either manually or automatically. There is no heat recovery equipment on the flue gas end. Fuel is fired through dual, parallel, frontwall 26-in. (0.66-m) Riley model B water-cooled mechanical spreader stoker feeders. The boiler is equipped with an alloyed oscillating grate stoker measuring 10 ft long by 9 ft wide (3.1 m by 2.7 m), for an effective grate area of 90 sq ft (8.4 m²). The stoker consists of two independent, self-cleaning, automatic/manual, heat-resisting alloy grate surfaces supported on reinforced cross-tee grid assemblies. Each is operated by separate drive and has front ash discharge to a plenum served by a manual/pneumatic removal

system. Combustion air is supplied by a four-duct system with 8.625-in. (219-mm) outside diameter (o.d.) main duct and 6.625-in. (168-mm) duct to undergrate. The air system includes eighteen 2.50-in. (64-mm) lines with 1-in. (25.4-mm) overfire nozzles in the backwall.

Active coal storage is achieved in an in-plant, steel, 700-ton (630-MT) capacity, nonpartitioned, parabolic ceiling bunker shown in general cross-section in Figure 3. The bunker is 96 ft (29.3 m) long, 16 ft, 11 in. (5.2 m) wide at the top, and 19 ft (5.8 m) deep. It has 16 outlets measuring 2.50 ft by 2.50 ft (0.8 m by 0.8 m) and spaced inline on 6-ft (1.8-m) centers beginning 3 ft (0.9 m) from each end. Coal typically is not stored in the bunker more than 3 days and averages about 1 day.

Fuel is delivered to the plant by truck or front-end loader from an outside storage yard nearby, and dumped through a grade-level grate into a receiving hopper approximately 8 ft (2.4 m) deep. The hopper

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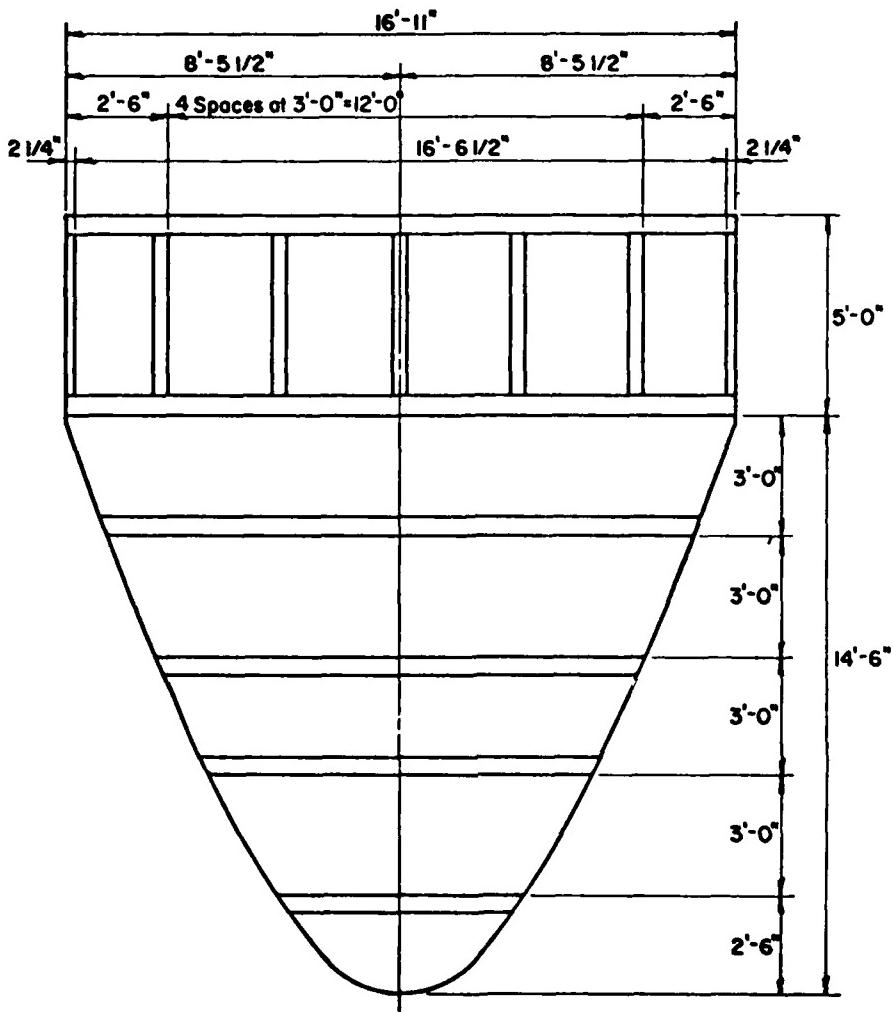
Figure 3. Bunker cross section, Fort Benjamin Harrison, IN.

discharges by gravity through a square outlet measuring about 1.5 ft by 1.5 ft (0.46 m by 0.46 m) directly to a hinged steel transfer conveyor which moves the fuel approximately 20 ft (6.1 m) to the bucket elevator which carries it about 50 ft (15.2 m) to the bunker. The fuel is distributed over the length of the bunker by a manually operated, rail-mounted, dual-discharge distribution system working on an 18-in. (0.5-m) wide rubber belt conveyor with approximately 1 in. (25.4 mm) unloaded working depth. Fuel is removed from the bunker by either of two rail-mounted weigh larries operated manually from the operating floor of the plant approximately 25 ft (7.6 m) below the outlets. From the weigh larries, the fuel is gravity discharged to the boiler frontwall feed hopper, from which it flows by gravity to the mechanical spreaders which feed it to the furnace. An outdoor ash silo

equipped with steam ejector serves all four boilers in the plant. Temperature, oxygen content, and opacity of the flue gases are continuously measured downstream from the induced draft fan.

Boiler preparations for the tests were minimal. Major air leaks were identified and many sealed with duct tape and glazing compound. K-type, chrome-alumel thermocouples were installed in the front and rear of each furnace sidewall and in one sidewall near the screen tube inlet. A USEPA Method 5 air pollutant emissions test and a plume observation were performed by personnel from the State of Indiana Air Pollution Control Board.

Table 1 shows the proximate and ultimate analyses of coal produced at the Central Utility Strip Mine in

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Montgomery, IN. The coal fired before and after the Woodex tests was not analyzed, but was assumed to correspond reasonably well to the tabulated properties. However, the coal appeared to be higher in fines than specified and to have accumulated a substantial quantity of free moisture from melting snow during outside storage.

Table 2 shows the proximate and ultimate analyses of Woodex typically produced in Knoxville, TN. The Woodex appeared to contain substantially less free moisture than the coal. Table 3 gives a sieve analysis of Woodex samples collected from the boiler frontwall feed hopper, and these data are fairly representative of the material delivered to the bunker. A unique characteristic of the Woodex was the relatively high fraction of fines; however, a final screening stage to reduce the fines content of the pelleted Woodex product was not in operation at the Knoxville Woodex plant when the test fuel was manufactured. Further, it appeared that many pellets broke up as they passed through the coal-handling system, both at the receiving hopper discharge to the transition conveyor (due to shear stresses on the pellets) and at the point where they fell about 17 ft (5.2 m) into the storage bunker.

The primary problem with Woodex was the large amount of dust it produced during delivery and handling. Approximately 40 tons (36 MT) of Woodex was delivered by truck, discharged directly to the receiving hopper, and conveyed to the designated coal-free area of the bunker. Considerable dust was generated where the fuel was unloaded from the trucks, and throughout the in-plant handling system as well. Plant personnel observed much dusting and pellet breakage where the receiving hopper discharged to the steel-hinged transition conveyor. Approximately 50 lb (23 kg) of material spilled from the transition and rubber belt conveyors above the bunker. It was observed that spillage from the belt conveyor could be lessened by resetting the rollers to provide greater working depth to the belt. High dust density was also observed in the bunker area during delivery; Table 4 gives a sieve analysis of dust collected from surfaces in the bunker area of the plant.

Few problems other than minor dusting and spilling of fines were noticed as the Woodex passed through the handling and feeding system at the Fort Benjamin Harrison plant. The fuel was stored in one end of the bunker in a pile measuring approximately 20 ft long by 11 ft wide by 10 ft high (61 m by 3.4 m by 3.1 m) and covering three outlets. Fuel density was determined to be between 0.50 and 0.67 of that of the coal regularly used at the plant. Testing commenced about 5 hours after fuel delivery, and no Woodex remained in the bunker longer than 36 hours. Some particle segregation by size was observed as the pellet/fines mixture was distributed into the designated area of the bunker, and there was a pronounced tendency of fines to adhere to the hopper walls and not flow freely to the outlet. At one point during the test, ratholing threatened continuous Woodex feeding and rodders were needed to restore gravity mass flow. No major problems were encountered in running the material through the weigh larry. Although some spillage of pellets and fines to the operating floor was observed, along with spillage of fines from the two mechanical feeders on the boiler, these problems might better be described as a housekeeping bother rather than an operating difficulty.

Combustion performance of substitute Woodex was generally satisfactory throughout the short-term test. During the pretest, the boiler was operated on Woodex up to 92 percent maximum capacity rating (MCR) with no apparent operational problems. During the second, more intensive test, the boiler was operated between 59 percent and 84 percent MCR, with the exception of turndown tests where the unit was operated below 28 percent MCR. Plant steam demand during the test was such that a second boiler had to be kept on-line, preventing operation of the tested boiler at greater than 84 percent MCR.

Thermal data taken during the test suggested a relative shift in duty between the radiant and convective sections and a loss of overall fuel-to-product (steam) efficiency when firing Woodex. At 72 percent MCR (normal boiler operating level), furnace gas temperatures when firing Woodex were on the order of 40°F (4°C) higher than when firing coal (1596°F [869°C] versus 1555°F [846°C]). Screen tube inlet temperature averaged 1297°F (703°C), or 3.8 percent higher than with coal. Stack gas temperatures averaged 619°F (326°C), or 6 percent greater than with coal, and the temperature drop across the convective section was approximately 2 percent greater than with coal. The oxygen content of flue gas varied between 10 and 11 percent, and relative air varied between 5.8 and 6.0, in contrast to values of 12.7 percent and 5.9 to 6.2, respectively, when firing coal. It was observed that flue gas oxygen content could have been reduced had the system been equipped with finer controls for underfire and overfire air. Since a boiler efficiency test was not conducted, no data are available on the

Table 1
Coal Properties, Fort Benjamin Harrison, IN

Proximate Analysis (Percent by Weight)

Moisture	10.80
Volatile Matter	37.30
Fixed Carbon	41.20
Ash	10.70

Ultimate Analysis (Percent by Weight)

Ash	10.70
Sulphur	4.90
Hydrogen	4.35
Carbon	61.52
Moisture	10.80
Nitrogen	1.25
Oxygen	7.18

Coal source: Central Utility Strip Mine, Montgomery, IN.
Data are averages.
Heating Value: 11,300 to 12,500 Btu/lb (26 273 to 29 063 kJ/kg) as-received.

Table 2
Woodex Properties, Fort Benjamin Harrison, IN

Proximate Analysis (Percent by Weight)

Moisture	4.3 -12.0
Volatile Matter	50.0 -71.0
Fixed Carbon	14.0 -19.0
Ash	0.3 - 3.2

Ultimate Analysis (Percent by Weight)

Ash	0.3 - 3.2
Sulphur	T- 0.1
Hydrogen	5.4 - 5.8
Carbon	46.5 -51.2
Moisture	9.3 -16.0
Nitrogen	0.03- 0.26
Oxygen	38.5 -39.8

Woodex source: Tennessee Woodex, Inc., Knoxville, TN.
Data are ranges of analyses.
Heating value: 8100 to 8800 Btu/lb (18 833 to 20 460 kJ/kg) as-received.
T = trace amount only.

Table 3
Sieve Analysis of Woodex, Fort Benjamin Harrison, IN

Particle Size		Percent
Microns	Inches	by Weight*
>2380	>0.09	60.93
1190-2380	0.05 -0.09	9.13
595-1190	0.023 -0.05	10.17
420- 595	0.0165-0.023	4.56
210- 210	0.0083-0.0165	8.09
149- 210	0.0059-0.0083	2.35
<149	<0.0059	4.29

*Error: + 0.48%

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Table 4
Sieve Analysis of Wood Dust,
Fort Benjamin Harrison, IN

Particle Size		Percent
Microns	Inches	by Weight
>420	0.0165	0.76
297-420	0.0165-0.0117	0.51
210-297	0.0083-0.0117	5.84
177-210	0.0070-0.0083	6.09
150-177	0.0059-0.0070	8.88
74-150	0.0029-0.0059	41.12
<74	<0.0029	36.79

change in efficiency when Woodex was used instead of coal. It is known that a major limiting factor is the volumetric flow rate of the combustion products. Separate studies on similar equipment point to efficiency losses of greater than 8 percent (82.52 to 74 percent) when substituting Woodex for coal.[9]

Flame temperature was measured with a portable, hand-held Leeds & Northrup optical pyrometer. Measurements were taken at the base of the flame from both sides of the boiler near both the front and rear walls. Flame temperatures when firing Woodex ranged between 2200°F and 2450°F (1204°C and 1343°C) and when firing coal between 2300°F and 2600°F (1260°C and 1427°C). Flame temperatures measured during this test compare to those taken at other installations when firing clean, plastic-bound, wood pellets in a boiler of comparable size.[10]

Flame travel during the test was observed through a reflecting glass from all four of the boiler's sidewall viewports. Little difference in length of flame travel was observed when Woodex was substituted for coal. However, particularly at loads above 75 percent MCR, a noticeable quantity of sparklers could be seen penetrating the screen tube free gas area. This phenomenon was attributed in part to the high fines content of the fuel and to the fines' light weight, which permitted them to readily entrain in the gas stream as they were fed to the furnace.

Throughout the test, the fuel bed generally remained stable and uniform, and exhibited a consistent, medium flame height. Some fluidization of the fuel bed was

[9]*Study of Alternate Fuels, Heating Plant for Major Support Area, Trident Submarine Base, Bangor Annex, Keyport, Washington* (Bumstead-Woolford Co., 1978).

[10]*Atmospheric Emission and Performance Evaluation of Frajon Full Pellet* (Alsid, Snowden and Associates, Bellevue, WA, 1978).

observed, but such occurrences were local and transient. It is noteworthy that fluidization happened near the lowest achievable rates of underfire air flow and could present an operating problem if plant controls cannot effectively minimize underfire air.

Throughout the test an even 1.5-in. (38-mm) bed of coal ash was maintained below the Woodex ash to ensure that grate materials were protected. Observations of the wood ash indicated that it had no apparent tendency to clinker or agglomerate, that it was finer and less compact than coal ash, and that it was generally evenly distributed across the grate (with the exception of a narrow field near the backwall where there was virtually no coverage—a condition not unusual when firing coal). There was no visually apparent evidence of tuyere blockage or localized overheating of grate materials.

Throughout the tests the Ringlemann opacity of the flue gases ranged between 0.2 and 0.3 for Woodex, 0.3 and 0.5 for coal, and 0.1 and 0.2 for blends consisting of 15 to 20 percent Woodex by volume. Indiana State Environmental Control Board personnel observed a smoke plume that appeared to comply with standards. However, USEPA Method 5 stack tests performed by Board personnel measured particulate emissions averaging 0.47 lb/MBtu (0.202 kg/GJ), which is greater than the proposed Indiana State Limit of 0.3 lb/MBtu (0.129 kg/GJ). Particulate emission rates at Fort Benjamin Harrison were well above the average of 0.28 lb/MBtu (0.120 kg/GJ) measured during a similar scale test using a clean, plastic-bound, wood pellet and a generally fines-free, wood-derived fuel.[11] Although noncompliant by State of Indiana standards, the particulate emission rate when firing Woodex was less than half of that measured when firing coal (0.96 lb/MBtu [0.413 kg/GJ]) and would require less efficient —and therefore perhaps less costly—flue gas cleanup equipment to attain compliance at the plant.

Three reasons are proposed for the unexpectedly high particulate emission rate during the test. First, the relatively high fraction of fines in the fuel, coupled with their low density compared to coal fines, was observed to readily entrain in the turbulent combustion gases as the fuel was mechanically injected into the furnace. Particles having a top size of less than 2380 microns (0.09 in.) represented, by weight of the fuel, approximately 40 percent of all fines, and

[11]*Atmospheric Emission and Performance Evaluation of Frajon Fuel Pellet.*
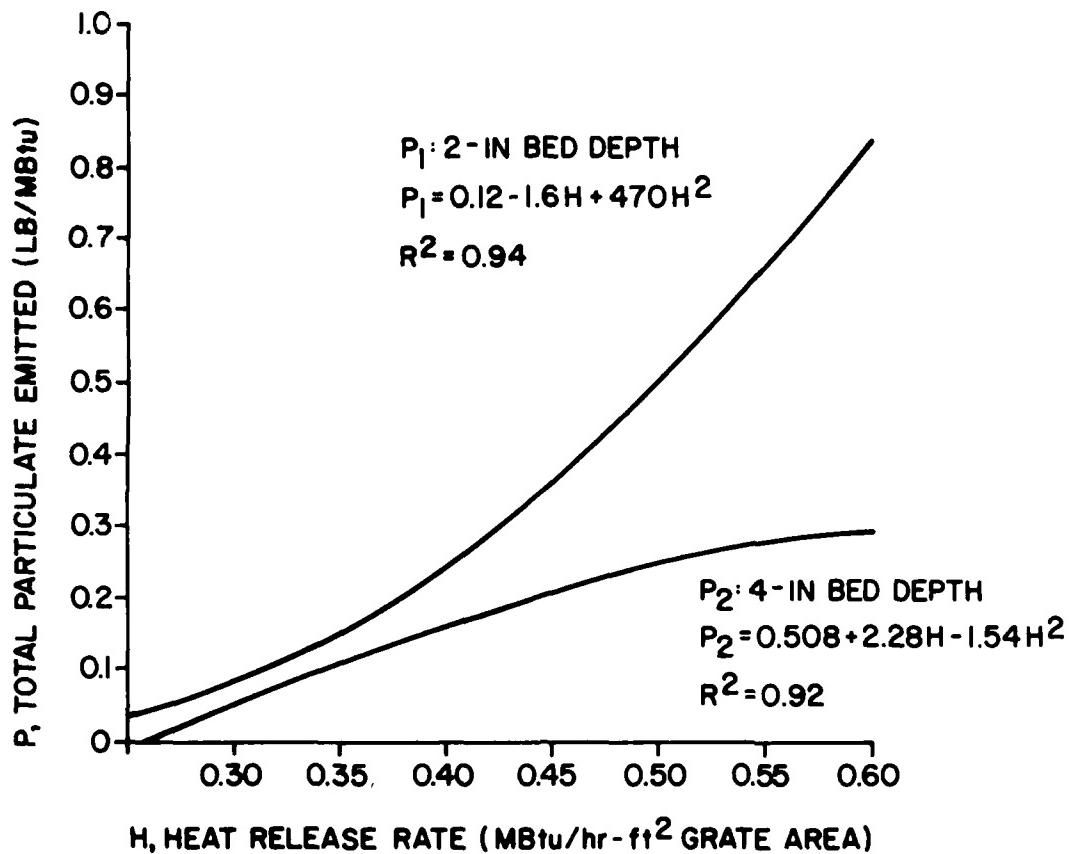
Figure 4. Relation of fuel bed depth to particulate emissions from wood-fired boilers.

a significant portion of these particles remained in suspension and were carried by the gas stream to the screen tubes. In the typical operation of a spreader-stoker firing a fuel for which it is designed, between 30 and 50 percent of the combustion takes place in suspension and the remainder on the fuel bed.[12] Assuming 30 percent of the balance of the Woodex burned in suspension, the total mass fraction of fuel combusted above the fuel bed can be conservatively estimated at 58 percent. Hence, there was a distinct shift in the relative roles of bed and suspension burning; the latter increased and probably resulted in greater fly-ash carryover. Second, little fly ash from the Woodex was removed from the flue gases by the mechanical collectors, which were designed for coal ash. Such collectors work on the principle of inertial separation of particulate from the carrier gas, and their efficiency is directly related to particle density; the heavier the particles, the greater the efficiency. Hence, the collectors' mass fractional removal efficiency will be less

when relatively light ash, such as generated from the combustion of Woodex, passes into them. Third, when wood is fired, fuel bed thickness (depth) has been shown to control particulate carryover (Figure 4).[13] Increasing the depth of the fuel bed can reduce the rate of fly-ash carryover, and there is even more reduction as the fuel-feed rate is increased. As Figure 4 shows, for a normal operating range of 0.45 to 0.55 MBtu/hr—sq ft (5.11 to 6.25 GJ/hr-m²) grate heat release rate, a fuel bed 4 in. (102 mm) deep could have resulted in emission rates compliant with the proposed Indiana State level of 0.3 lb/MBtu (0.129 kg/GJ). During the Woodex test, however, feeder-turnup rate was the limiting factor because it was not possible to increase the fuel-mass flow rate to the furnace beyond the point where a fuel bed about 1.5 in. (38.1 mm) deep would accumulate. It was observed that larger capacity feeders operating on a fuel significantly lower in fines could have achieved

[12]*Stokers for Industrial Boilers — Assessment of Technical, Economic, and Environmental Factors, PB288689* (Battelle-Columbus Laboratories, 1975).

[13]K. Tuttle and D. Junge, "Combustion Mechanisms in Wood Fired Boilers," *Journal of the Air Pollution Control Association*, Vol 28, No. 7 (July 1978).

the desirable fuel-bed depth and an attendant reduction in fly-ash carryover.

Tests at Fort Benjamin Harrison indicated that pelleted wood fuel could be used economically as a coal substitute at the Central Heating Plant. The fuel tested was purchased at a truck-delivered cost of $62.50/ton ($69.44/MT), which included $36.50/ton ($40.56/MT) shipping. The fuel had a heating value of about 8400 Btu/lb (19.5 mJ/kg). Hence, of its total delivered cost of $3.72/MBtu ($3.93/kJ), $2.17/MBtu ($2.29/kJ) was for shipping, and $1.55/MBtu ($1.64/kJ) was the cost f.o.b. the site of manufacture. Coal is currently procured by Fort Benjamin Harrison at a delivered cost of $1.71/MBtu ($1.80/kJ). A reliable, locally available supply of pelleted wood fuel could compete economically with coal on a delivered-cost basis.

Summary
Relatively moderate-term use of pelleted (densified) wood fuel at Kingsley AFB and the short-term tests conducted at Fort McCoy, Fort Benjamin Harrison, and Rock Island Arsenal have shown some of the major conditions affecting use of the alternate fuel across the entire coal system spectrum.

The performance of pelleted wood fuel in handling and storage systems designed for coal has been generally satisfactory. However, the fuel is very sensitive to moisture and therefore needs enclosed storage. This requirement may either limit the quantity of fuel delivered to a plant at any given time if the installation uses only storage presently available, or may add to the cost of introducing the fuel if the installation must build a new, enclosed, storage structure. Although drying and pelleting wood is one way to make more economical its transport, handling, and use, pellets may fall at least partial victim to the technical limits that have long shackled development of large-scale, wood-fired boilers: the handling and storage technology required for relatively large-scale use of pelleted wood is still far behind the technology required for its proper combustion.[14] This could potentially limit the use of pelleted wood fuel at larger Army heating and power plants.

Dusting and spillage have presented problems when wood pellets pass through coal-handling systems.

Although dust concentrations thus far probably have not presented explosion hazards, dust could have jeopardized the health of plant personnel. Dusting was effectively reduced at Rock Island Arsenal by a light water spray over the pellets as they were being conveyed to a bunker after delivery, and worker safety was ensured by having employees follow established operating procedures and wear filter masks and safety glasses. Reduced fines content in the delivered fuel also could reduce dusting problems. Despite the dust, plant personnel are nearly unanimous in their preference for wood pellets over "dirtier" coal.

Few problems have been encountered with bunker storage of the wood pellets. However, such storage has typically been brief and has involved relatively small quantities of fuel. Particle segregation by size has been observed during several tests as the pellets have been distributed into a bunker, but standard engineering procedures and equipment exist for remixing segregated solids and ensuring uniformity of discharge.[15] However, remixing fuel may not be desired, particularly if fines will be a problem; in other words, natural forces may segregate some potentially troublesome fines. Fines are also at the root of many no-flow problems encountered in hoppers, since they effectively increase the bulk strength of the solid (as measured as internal angle of friction). Other factors such as bunker geometry, outlet size, and materials of construction determine whether a coal-designed bunker will reliably handle any alternate fuel.[16] A wide variety of bunker designs exists in Army heating and power plants, and a bunker's capability to handle wood pellets reliably must be determined on a case-by-case basis. Chapter 4, which gives design parameters for a wood pellet storage and feeding system, provides general guidelines for such a determination.

Combustion performance of wood pellets has differed significantly from that of coal. Pellets contain more volatile matter, less fixed carbon and ash, and somewhat more moisture than most bituminous coals. Moreover, cellulosic material volatilizes and ignites more rapidly than coal at a given furnace temperature, and will volatilize and ignite at temperatures about 302°F

[14] *Wood Energy for Small Scale Power Production in North Carolina* (Ultrasystems, Inc., 1978).

[15] J. Johanson, "Design for Flexiblity in Storage and Reclaim," *Chemical Engineering* Vol 85, No. 24 (October 30, 1978), pp. 19-20.

[16] A. Jenike, *Gravity Flow of Bulk Solids* (University of Utah. Engineering Experiment Station, 1961).

(150°C) less than Midwest Bituminous Coal.[17] Accordingly, when wood pellet-coal blends are fired, the pellets can tend to quench coal combustion, resulting in clinkering and excessive smoke. Operating adjustments to accommodate firing substitute pellets have included increasing the fuel feed rate and modulating overfire and underfire air. In many cases, the desirable low level of underfire air flow has not been achievable because the boilers tested lacked the fine controls for such modulation. In other cases, it has not been possible to achieve adequate overfire velocity and distribution to provide sufficient turbulence, and hence residence time, for the wood fuel (particularly fines) to combust completely in the radiant furnace chamber. Nevertheless, wood pellets have been used successfully as a coal substitute at boiler loads ranging from 0.28 to 0.85. A major limiting factor has been the volumetric flow rate of the flue gas, which is larger for wood pellets than for coal. Moreover, pellet firing in a boiler designed for coal is accompanied by a shift in relative duty between the radiant and convective heat exchange sections and a probable drop in boiler fuel-to-product conversion efficiency.

Since firing wood pellets appears to generate both less ash and finer ash than coal, the depth of ash bed needed to protect grate materials from (radiant) thermal stress is of some concern. Special alloys may need to be used as grate material when switching from coal to pellets. Plant personnel where wood pellets have been tested believe wood ash is more easily handled by pneumatic systems than coal ash and leads to reduced wear both of pneumatic lines and of internal boiler surfaces. Since the ash is aerodynamically light, though, it readily entrains in combustion gases and is difficult to remove with control devices working on the principle of inertial separation from carrier gas.

Whether wood pellets will meet air pollutant emissions limitations everywhere is presently speculative. Emissions of sulphur oxides and nitrogen oxides should not be a problem since the fuel contains negligible sulphur, and flame temperatures are relatively low. Particulate emissions across all tests have ranged from compliant to noncompliant, but unanimously have been on the order of half of what usually is

encountered when firing coal. Hence, if control equipment must be added when firing wood pellets, it may be a less efficient and lower cost device than high-efficiency, high-cost systems such as baghouses.

Economically, it appears that wood pellets can compete with coal on a delivered cost basis provided there is a supply of pellets nearby. Coal costs range from \$1.38/MBtu to \$2.18/MBtu (\$1.31/kJ to \$2.06 kJ) at the test locations mentioned above. Pelleted wood fuel has been purchased at a delivered cost ranging from \$2.17/MBtu to \$5.56/MBtu (\$2.07/kJ to \$5.28/kJ) across all locations. However, the cost of wood pellets f.o.b. site of manufacture has had a relatively small range, between \$1.43/MBtu and \$1.73/MBtu (\$1.36/kJ and \$1.65/kJ). While delivered costs of wood pellets are essentially above the range of coal costs, their as-produced costs lie well within those of coal. Hence, under current regulations governing transport of pelleted wood fuel, transportation distance is a major factor in limiting its price competitiveness with coal.

3 DENSIFIED BIOMASS PRODUCTION

General

Several different densified biomass production processes are now in operation throughout the world. Their common features include the capacity to remove moisture from virgin or as-harvested raw material and to create an appropriate form of fuel that can be handled, stored, and burned in a system designed for another fuel. In the case of wood, the as-harvested moisture content can be as high as 50 percent by weight; reducing this will not only improve its effectiveness as a fuel, but also will make its transport more economical since the weight of "unproductive" masses of water will not be moved with the fuel. Fuel form is dictated by the needs of the system in which the material is a possible substitute or supplemental fuel. In some applications, dry pulverized biomass can be used effectively in its loose or unconsolidated form using state-of-art burner technology retrofitted to a boiler.[18] For use in most installation-scale central heating and power plants equipped with mechanical stokers to fire coal, the fuel must be pelleted to resemble coal in general form.

[17] *Reactivity and Gasification Characteristics of Low Ranking Coals and Potentially Reducing Waste Materials* (Pittsburgh Energy Research Center, 1976); S. A. Hathaway and J. Lin, *Thermogravimtric Analysis of Solid Refuse-Derived Fuels and Coal*, Technical Report E-149/ADA067829 (CERL, March 1979).

[18] *Solid Fuel Burners* (Peabody Gordon-Platt, Inc., 1979).
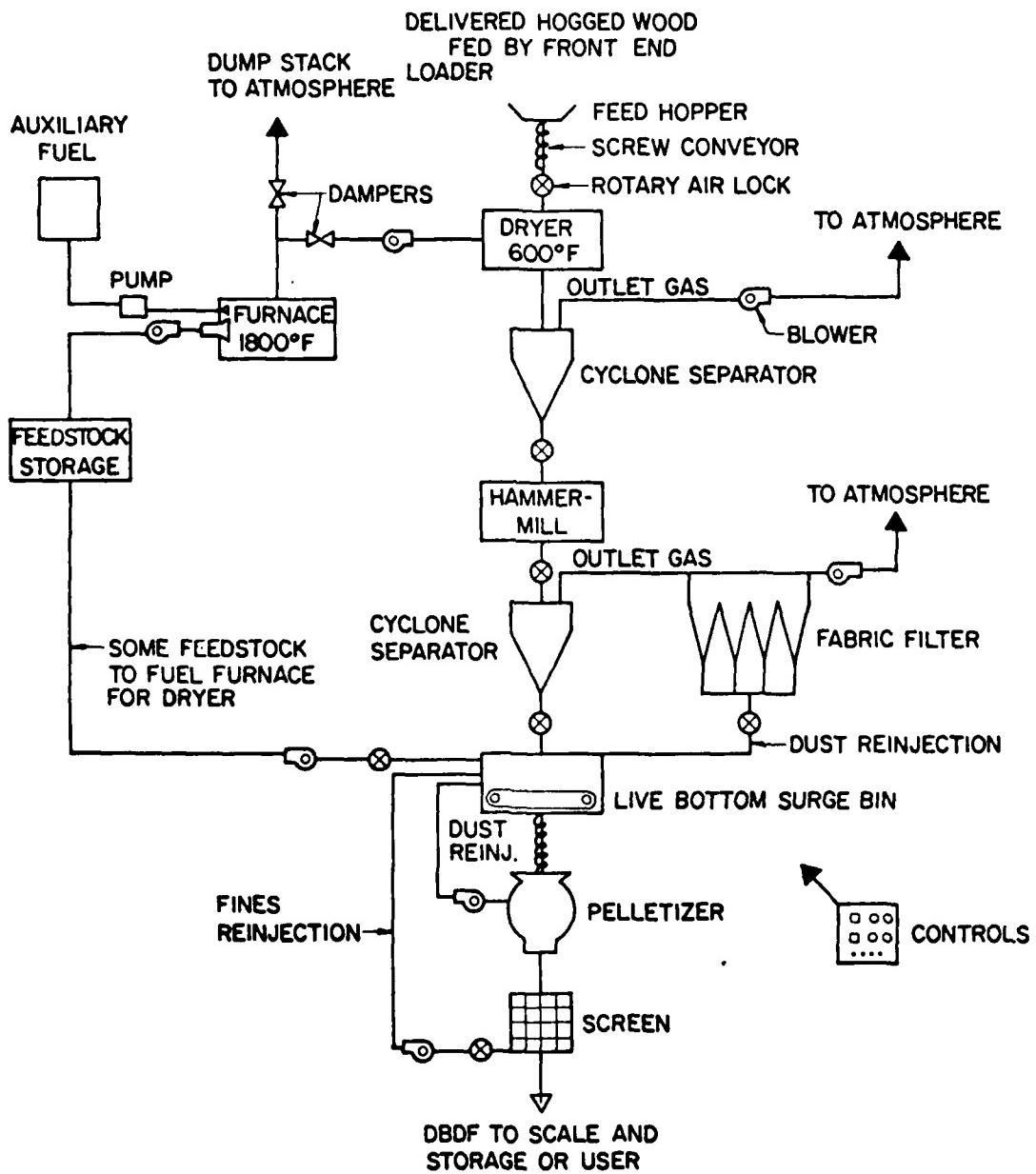
Figure 5. Wood pellet production process

Production Process

A typical wood pellet production process is illustrated in Figure 5.[19] Important unit operations are drying, shredding, pelleting, and screening. While pelleting and screening are always the final unit operations, some plants shred first then dry, while others dry then shred. The sequence depends on the nature of the delivered material, which normally is hogged or chipped wood from a mobile operation working forested land. If the material has a high moisture content, initial drying prevents useless mass from entering the shredder. Conversely, dryer efficiency is partly related to material particle size and is apt to be somewhat improved when the equipment is operating on shredded material rather than coarse grade input.

Pellets with an as-fired heating value ranging between 8000 and 9000 Btu/lb (18 603 to 20 929 mJ/kg) and having a moisture content on the order of 12 percent by weight are produced from such a process. An average Army boiler producing 40,000 lb/hr (18 144 kg/hr) steam would thus require between 80 and 90 tons/day (72 and 81 MT/day) wood pellets as fuel. For a typical 3-day active fuel storage time, approximately 250 tons (225 MT) must be stockpiled. The requirement for larger plants will increase proportionately. Few Army heating or power plants exceed 200 MBtuh (59 MWt) total input capacity, equivalent to a daily wood pellet requirement of about 300 tons (270 MT).

Equipment and Functions

A typical wood pellet production plant includes conveyors, feeders, a dryer, a furnace to provide heat for the dryer, a shredder, a surge bin, a pelleter, a screen, cyclone separators, and a fabric filter. Equipment can be housed in a pre-engineered building on poured concrete slab in most climates. Special foundations are usually required for heavier process equipment.

A typical plant contains a receiving area to accept deliveries of raw material (hogged or chipped wood), which is moved by a front-end loader or conveyer (if a live bottom receiving hopper is selected) to the dryer (or shredder if this is placed first). Heat for the dryer is supplied by a furnace firing a fraction of the fuel taken from either a downstream separator or the surge bin.

The feedstock is conveyed pneumatically from the dryer through a cyclone separator to the shredder. A typical shredder is a horizontal shaft hammermill with between 250 and 350 connected horsepower (186 and 261 kWe). Additional moisture is lost in the shredding operation, along with small amounts of dust. From the shredder, feedstock is conveyed to a live-bottom surge bin where it is held on a first-in, first-out basis. A pneumatic conveying system can be used, in which case a cyclone separator must be installed, along with a fabric filter to remove fine dust from cyclone outlet air before it is released to the atmosphere. Traditional belt conveyors can also be used, but caution must be exercised in their design or selection to prevent excessive dusting and spilling of the feedstock.

The surge bin functions as a load leveler for downstream equipment and as temporary storage of partially processed feedstock. A typical surge bin is the live bottom drag conveyor type, which feeds material to a plenum along its front wall. A constant pitch and flight screw conveyor in the plenum feeds the material to the pelletizer inlet hopper. A fraction of the feedstock is taken (usually pneumatically) from the surge bin and used to supply the furnace for the dryer. Fines collected from a downstream pellet screening operation and dust collected in the fabric filter can be reclaimed and cycled to the surge bin to join the feedstock.

Several types of pelletizers are commercially available; these include mechanical extrusion mills, cubetters, roller-compressors, and screw extruders. Many companies opt for mechanical extrusion devices with replaceable dies. Capacities ranging from 1 to 5 tons/hour (0.9 to 4.5 MT/hr) are available. The mill typically requires from 250 to 350 connected horsepower (186 to 261 kWe). Experimentation and actual operation have indicated that pelletizers operate best on a feedstock containing between 10 percent and 18 percent moisture by weight and at temperatures ranging from 210°F to 260°F (99°C to 127°C). Water in the feedstock acts as a heat sink to prevent the pellets from being scorched in the densification process. A small steam vent is necessary, and sometimes dust collection equipment is required.

Binders such as pitch and, more recently, environmentally clean scrap plastic have been used to improve the handling characteristics of wood pellets.[20] Binders

[19]"Personal communication with Mr. Duane Schaub, Guaranty Performance Co., Independence, KS, 22 March 1979.

[20]"Atmospheric Emission and Performance Evaluation of Fra jon Fuel Pellet (Alsid, Snowden and Associates, Bellevue, WA, 1978).

are added to the wood pellet feedstock through a metering feeder on the densification mill. Combustible binders may enhance the combustion performance of the pellet but could also place limitations on storage equipment and residence time, particularly because of the possibility of "leakage" and migration of the binding agent.

After the pelletizer, the wood pellets are mechanically conveyed to a screen to remove fines, which are returned to the surge bin. Numerous screening devices are commercially available, ranging from simple shakers to more complex air scalpers. Care must be exercised in screen selection, since the hot pellets coming from the pelletizer remain rather fragile until they cool. This is partly because lignins in the feedstock are liberated under heat and must cool before they can function effectively as a natural pellet binder. Pellets normally are weighed before being sent either to storage or to the user.

A typical wood pellet production line includes controls which can be operated both in automatic and manual modes. Normally, all operations are visible from the central control console. Safety interlock systems are recommended, along with lockable master switches near all major equipment. Fire extinguishers, a master sprinkler system, and remote alarms are recommended.

Energy Analysis

Energy analyses of wood pelleting operations indicate that pelleted wood fuel can be produced for about 181 kWh/ton (716 mJ/MT) input material or 328 kWh/ton (1298 mJ/MT) output. Table 5 gives average energy balance data for a wood pellet production operation. The data are based on a 3-shift/day operation receiving 120 tons/day (108 MT/day) of hogged bark and wood having a moisture content of 50 percent by weight. The operation is assumed to produce 66 tons/day (59 MT/day) wood pellets having a moisture content of 10 percent by weight and a heating value of 8350 Btu/lb (19 417 kJ/kg). The data shown are averages indicative of general operation and the relative magnitude of energy consumption by major individual unit operations.

Primary energy consumers are the hammermill, pelletizer, and dryer. Total connected power can range between 1000 and 1400 HP (746 and 1044 kWe). At approximately 300 HP (224 kWe) each, the hammermill and pelletizer together account for about 50 percent of the connected power requirement.

The energy analyses of wood pellet production indicated an overall efficiency of 85.3 percent, which is somewhat less than conclusions reached by the Solar Energy Research Institute (SERI) in a similar analysis of a 300 ton/day (270 MT/day) bark pellet plant.[21] SERI reported a process energy efficiency of 92.8 percent for a hypothetical plant consisting of six hammermills, two pelletizers, and a dryer coupled with a wood gasifier, to produce pellets having a moisture content of 10 percent by weight and a heating value of 8000 Btu/lb (18 603 mJ/kg). Neither the SERI analysis nor this investigation considered the energy cost of harvesting, transporting and chipping the raw material delivered to the pellet production plant. Such a determination was outside the scopes of both studies.

The efficiency of the wood pellet production process is somewhat misleading, since "efficiency" is not used here in a conventional sense. The efficiencies of 85.3 percent determined in this investigation and 92.8 percent determined by SERI are merely a second way of presenting the fact that the energy added to the delivered material (listed as Energy Input in Table 5) is partially recovered in the product pellet. For example, the energy required for drying appears as an input. The larger fraction of this input is the energy required to evaporate water. Approximately 66 percent of the energy using for drying is recaptured in the pellets' increased heat of combustion. It is important to note also that although drying is a major energy user, it greatly increases combustion equipment capacity, improves heat transfer in a boiler, and reduces emissions of air pollutants.[22]

Product Characteristics

The production and use of wood pellets can be viewed in the context of a classical fuel substitution problem. At an installation where wood is available as an energy resource, the military manager must choose the most effective way to use it. The alternatives typically confronting him are: (1) constructing new equipment (usually a plant) to store, handle and fire relatively unprocessed material (chips or hogged wood); or (2) investing in wood processing equipment to produce a fuel usable in an existing plant. In a

[21]T. Reed and B. Bryant, *Densified Biomass: A New Form of Solid Fuel*, SERI-35 (Solar Energy Research Institute, 1978).

[22]R. Arola, *Wood Fuels — How Do They Stack Up?* (Energy and the Wood Products Industry, Forest Products Research Society, Madison, WI, 1976).

	Connected Electrical (kW)	Total Energy Consumed MBtu/day (GJ/day)
Energy Input		
Front End Loader	N.A.*	9.0 (9.5)
Dryer		
Feedstock as Fuel	N.A.	75.0 (79.1)
Auxiliary Fuel	N.A.	4.5 (4.7)
Drives	97.7	8.0 (8.4)
Hammermill	224.6	18.4 (19.4)
Pelletizer	224.6	18.4 (19.4)
Motors		
(Incl. Blowers, Pneumatics)	238.1	19.5 (20.6)
General		
(Incl. Lighting Controls,		
Safety System	119.6	9.8 (10.3)
Total	904.6	162.6 (171.6)
Energy Output		
Wood Pellets		
(66 tons, 8350 Btu/lb, 10% H₂O)	N.A.	1102.2 (1162.9)
(59.86 MT, 19.05 MJ/kg, 10% H₂O)		

Efficiency

$$100 \times \left(\frac{1102.2 - 162.6}{1102.2} \right) = 85.3$$

*Not applicable.

growing number of cases, wood pellets are becoming available to installations, and this presents yet a third alternative. The decision to produce or procure wood pellets is based on economics, which, in turn, depends upon what costs are associated with ensuring the pellets' reliable, proper performance in a heating or power system designed for another fuel, such as coal. The classical fuel substitution approach requires that the extent to which a virgin energy resource must be processed for effective use be determined by the characteristics of the particular heating or power system chosen for conversion. Such an approach is nearly always taken when converting gas- or oil-fired plants to coal, but such has not been entirely the case with wood pellets, where experience to date has focused on short-term testing of a product which recently entered the market as a widely advertised coal substitute.

The objectives of the wood pellet production processes now in operation are to reduce the moisture content of virgin wood and to convert it into a form which will perform properly in systems designed for coal. Moisture content and form are important fuel variables which directly influence fuel performance in boilers.

The moisture content of raw wood is variable and significant in terms of the material's fuel potential.[23] It usually varies between 20 and 55 percent by weight, and can be as high as 67 percent on an as-received basis. Moisture content also varies with species, tree age, and tree material. Hardwoods contain an average of 30.2 percent by weight moisture, while softwoods contain an average of 46.1 percent. Young trees contain more moisture than those which have passed their growth rate peak. Foliage (leaves, needles, and branches) contains more moisture than the bole, and, within the bole, sapwood contains more water than the heartwood. Conversely, nearly all coals contain

[23]D. Tillman, *Wood as an Energy Resource* (Academic Press, 1978).

Table 6
Chemical Analysis of Fuels

Fuel		Proximate Analysis			Ultimate Analysis						Heating Value (Dry):
	Moisture	Volatile Matter	Fixed Carbon	Ash	C	H	O	N	S	Ash	Btu/lb (MJ/kg)
E. Hemlock	Dry	72.0	25.5	2.5	53.6	5.8	37.9	0.2	T	2.5	8885 (20.648)
W. Hemlock	Dry	74.2	23.6	2.2	50.4	4.8	41.4	0.1	0.1	2.2	8620 (20.032)
Douglas Fir	Dry	82.0	17.2	0.8	52.3	6.3	40.5	0.1	T	0.5	9050 (21.031)
Pine Bark	Dry	72.9	24.2	2.9	53.4	5.6	37.9	0.1	0.1	2.9	9030 (20.985)
Spruce Bark	Dry	69.6	26.6	3.8	51.8	5.7	38.4	0.1	0.1	3.8	8740 (20.311)
Oak Bark	Dry	76.0	18.7	5.3	49.7	5.4	39.3	0.2	0.1	5.3	8370 (19.451)
Pine Sawdust	Dry	79.4	20.1	0.5	51.8	6.3	41.3	0.1	T	0.5	9130 (21.217)
Wood Pellets (Pine)	Dry	78.6	21.0	0.4	46.9	6.1	46.4	0.1	T	0.4	8222 (19.107)
IL Bituminous Coal	Dry	46.3	45.1	8.6	62.8	5.9	17.4	1.0	4.3	8.6	13,050 (30.327)
PA Bituminous Coal	Dry	21.2	72.6	6.2	80.7	4.9	5.3	1.1	1.8	6.2	14,800 (34.394)
Urban Solid Waste	Dry	66.6	12.8	20.6	43.3	6.1	28.9	0.9	0.2	20.6	6200 (11.406)

Proximate and ultimate analysis as weight percent, dry basis.

T = trace amount.

*Sources: *Combustion Engineering* (Combustion Engineering Corp., 1966); *Steam* (Babcock and Wilcox Corp., 1976); *Study of Alternate Fuels, Heating Plant for Major Support Area, Trident Submarine Base, Bangor Annex, Keyport, Washington* (Bustead-Woolford Co., 1978); M. Smith and K. Stinson, *Fuels and Combustion* (New York, 1952); W. G. Wilson, *Handbook of Solid Waste Management* (Van Nostrand-Reinhold, 1978).

less than 10 percent moisture, a notable exception being some lignites.

The relatively high moisture content of younger trees and of the foliage of nearly all trees suggests that moisture content will play an important role affecting the feasibility of wood fuel systems.

The highly variable moisture content of wood is one reason the chemical analysis of wood (reported as ultimate and proximate analyses) is usually presented on an air-dry basis (12 to 15 percent by weight moisture), oven-dry basis (5 to 8 percent), or moisture-free basis. Table 6 presents average chemical analyses of several fuels, including wood, wood pellets, coal and urban solid waste.[24] All data are given on a dry (moisture-free) basis, and they suggest that wood can be considered a fuel of intermediate properties between coal and solid waste. Premium fuels are those in which hydrogen and carbon contribute significantly to the energy content.[25] The combined hydrogen and

carbon content of natural gas totals about 100 percent by weight of the fuel. For bituminous coal, the tabled data show total carbon and hydrogen contents ranging between 68.7 and 85.6 percent. For wood, this range is between 53.0 and 59.4 percent, and for solid waste the total is 49.4 percent.

The average data in Table 6 indicate that wood pellets closely resemble wood in chemical composition and heating value on a moisture-free basis. In other words, changing as-delivered wood material into pellets reduces the material's moisture content (neglecting insignificant volatile losses during high-temperature drying and pelleting). By reducing moisture content, however, the process elevates the relative mass fractions of volatile matter, fixed carbon, and ash, and also relatively raises the heating value of the material. Pound-for-pound, then, drier wood has a higher energy value than wood containing a greater mass fraction of moisture. Removal of moisture is therefore one way of increasing the energy density of the fuel.

The energy density is further increased by pelleting the dried, shredded feedstock. The bulk density of as-received hogged wood can vary between 15 and 25 lb/cu ft (240 to 400 kg/m³). At an as-received heating value of 5500 Btu/lb (12 790 kJ/kg), the material's energy density varies between 82,500 and 137,500 Btu/cu ft (3653 and 6089 mJ/m³). Removing most

[24]*Combustion Engineering* (Combustion Engineering Corp., 1966); *Steam* (Babcock and Wilcox Corp., 1976); *Study of Alternate Fuels, Heating Plant for Major Support Area, Trident Submarine Base, Bangor Annex, Keyport, Washington* (Bustead-Woolford Co., 1978); M. Smith and K. Stinson, *Fuels and Combustion* (New York, 1952); D. G. Wilson, *Handbook of Solid Waste Management* (Van Nostrand-Reinhold, 1978).

[25]D. Tillman, *Wood as an Energy Resource* (Academic Press, 1978).

moisture and densifying (pelleting) hogged wood feedstock, produces a pellet which has a bulk density of 35 lb/cu ft (560 kg/m³) and a heating value on the order of 8100 Btu/lb (18 836 kJ/kg). The energy density of the product pellet is hence 283,500 Btu/cu ft (12 554 mJ/m³), or more than twice the energy density of the delivered raw material.

Although the energy density of wood pellets is far greater than that of hogged wood, it is still significantly lower than that of most coals. Coal with a bulk density of 45 lb/cu ft (721 kg/m³) and a heating value of 11,000 Btu/lb (25 579 kJ/kg) has an energy density of 495,000 Btu/cu ft (21 920 mJ/m³), which is about 75 percent greater than that of wood pellets and from 260 to 500 percent greater than that of hogged wood.

Consistency of moisture content is another important characteristic of wood pellets. Moisture content of raw wood is highly variable, but the wood pellet production process yields a product whose essential characteristics (ultimate and proximate analyses and heating value) are relatively consistent and therefore predictable. Moisture content can be expected to vary between 10 and 15 percent by weight. On a dry basis, volatile matter will vary between 69 and 78 percent, fixed carbon between 18 and 25 percent, and ash between 0.1 and 2.5 percent. The carbon/hydrogen ratio will usually be on the order of 8 or 9, the oxygen content about 40 percent, and both nitrogen and sulphur less than 1 percent. Wood pellets can be expected to have a heating value on the order of 8200 Btu/lb (19 068 kJ/kg) and a loose bulk density of about 35 lb/cu ft (560 kg/m³). With proper screening of the pelleted product, fines can be held to a minimum. And with state-of-the-art densification technology, pellets can be produced which compare in size to nearly any stoker coal.

Economics of Production

Table 7 shows typical ranges of capital costs and annually recurring cost items for a wood pellet plant receiving 120 tons/day (108 MT/day) of hogged wood. These data are presented to indicate the general range of costs which can be anticipated when planning a wood pellet production plant.

Capital costs are in FY80 (first of year) dollars and exclude site preparation, supporting facilities, design, contingency, startup and other items normally included when planning military construction. Discussions with wood pellet manufacturing personnel indicate that a turn-key plant receiving 100,000 tons/year (91 000 MT/yr) of hogged wood requires an investment of between $1,100,000 and $1,300,000.[26] The upper limit is equivalent to about $3380/ton/day ($3715/MT/day) process input capacity, based on a three-shift operation 5 days per week.

The line-item data for annual costs shown in Table 7 indicate that, from the production point of view only, the cost and consumption rate of electrical power are the most significant factors driving the economics of wood pelleting operations. This fact is evident in Table 8, which gives an annual cost analysis of a plant receiving 120 tons/day (108 MT/day) of hogged wood, where power comprises about 46 percent of the total annual cost. The data in Table 8 do not include depreciation, amortization, insurance and taxes. Nor do the data include the cost of delivered raw material. Based on Table 8, wood pellets can be produced for $17.74/ton ($19.72/MT), FY80 first-of-year dollars, at a minimum. This is a minimum production cost of approximately $1.06/MBtu ($1.01/kJ), which compares reasonably well with the as-vended, f.o.b. site of production costs reported earlier: $1.43 to $1.73 MBtu ($1.36 to $1.65/kJ).

A somewhat different picture is obtained when the cost of raw material is factored into the analysis. The current average delivered cost of locally available hogged wood is about $6.00/ton ($6.67/MT). This cost is directly passed on to the wood pellet consumer, elevating the minimal, as-produced wood pellet cost mentioned earlier from $17.74/ton ($19.71/MT) to $23.74/ton ($26.38/MT). In some locations, the cost of hogged wood and chips is rising rapidly in response to increased demand. One location experienced an unforeseen increase from $5.00/ton ($5.56/MT) to $12.00/ton ($13.33/MT).[27] At this higher cost of raw material, the as-produced cost of wood pellets becomes $29.74/ton ($33.04/MT), or $1.78/MBtu ($1.70/kJ). This is equivalent to a coal cost of $39.16/ton ($43.51/MT). At a delivered cost of $12.00/ton ($13.33/MT), enough hogged wood and/or chips to supply a 120 ton/day (108 MT/day) pelleting plant would cost $374,400/year—a figure which alone is approximately 23 percent greater than all other wood pellet production operation and maintenance costs presented in Table 8.

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[26]Personal communication with Mr. J. Galyon, Tennessee Woodex Inc., Knoxville, TN, 4 April 1979.

[27]Personal communication with Ms. M. Helms, Minnesota Department of Corrections, St. Paul, MN, 7 May 1979.

Table 7
FY80 Economics of Wood Pellet Production (120 Tons/Day [108 MT/Day] Input)

Item	Installed Capital Cost ($)	Power: HP (kW)	Water: GPM (m³/min)	Labor (# Workers)	Maint. & Repair (% of Cap. Cost, $)	Aux. Fuel: GPH (m³/min)	Vehicle Fuel: GPH (m³/hr)
Front End Loader	13,000-20,000	0 (0)	0	1	3	0	2-3 (0.008-0.012)
Rotary Dryer	15,000-40,000	40-60 (30-45)	0	½	3	0	0
Furnace	40,000-65,000	30-50 (22-51)	0	½	2½	1-2 (0.004-0.008)	0
Hammermill	180,000-250,000	250-350 (186-261)	0	½	4	0	0
Cyclone	9,000-15,000	25-40 (19-30)	0	0	2	0	0
Fabric Filter	12,000-95,000	30-55 (22-41)	0	½	4	0	0
Surge Bin	3,000-10,000	15-25 (11-19)	0	0	1¾	0	0
Pelletizer	80,000-110,000	250-350 (186-261)	0	½	4	0	0
Screen	20,000-42,000	15-35 (11-26)	0	½	3	0	0
Pneumatics	70-90/ft (230-295/m)	25-55 (19-41)	0	0	2½	0	0
Conveyors	30-60/ft (98-197/m)	10-25 (7-19)	0	0	2	0	0
Buildings (Incl. Mech. & Elec.)	27-40/sq ft (290-420/m²)	0 (0)	0	0	1½	0	0
General Plant Reqs	—	7-18* (5-13)	15-30 (0.06-0.12)	½	1	1-4* (0.004-0.016)	0
Summary	950-1400	697-1063 (520-793)	15-30 (0.06-0.12)	3½	2.6	2-6 (0.008-0.024)	2-3 (0.008-0.012)

*Includes heating and cooling.

Summary

Wood pellets can be produced from hogged wood or wood chips using proven commercial technology, as shown by the increasing number of wood pelleting operations being started across the country. The objectives of producing pellets include reducing the moisture content of as-delivered material and putting the material into a form that can be used effectively across the entire spectrum of unit operations in a heating or power system designed for coal.

Energy required to produce wood pellets is about 181 kWh/ton (716 mJ/MT) input, or about 328 kWh/ton (1298 mJ/MT) output. And most energy is consumed by shredding and densification (pelleting) operations, which together account for nearly 50 percent of a plant's electrical power usage.

Wood pellets have controllable, consistent, and predictable characteristics, as measured by proximate and ultimate analyses and heating value. The heating

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Item	Quantity	Unit Cost	Yearly Cost ($)
Electrical Power	1000 HP (745.7 kW)	$0.03/kWh	139,595
Water	25 GPM (0.094 m³/min)	$0.050/kgal ($0.013/m³)	4,680
Auxiliary Fuel (Oil)	5 GPH (0.019 m³/min)	$0.40/gal ($106/m³)	12,480
Vehicle Fuel (Diesel)	2½ GPH (0.0095 m³/min)	$0.65/gal ($172/m³)	25,350
Labor			
Supervisor	1 man-year	$35,000	35,000
Driver	1 man-year	$27,000	27,000
Operator	1 man-year	$27,000	27,000
Maintenance	½ man-year	$22,500	11,250
Maintenance and Repair (2% of $1,100,000)			22,000
Total			304,355

Per-Ton Cost:
66 tons/day (60 MT/day) (Table 5) x 260 = 17,160 tons/yr (15 560 MT/yr)
$304,355/17,160 = $17.74/ton ($19.55/MT)

*Assumes operation 3 shifts/day, 5 days/week, 52 weeks/year.

value of wood pellets is on the order of 8200 Btu/lb (19 068 kJ/kg). The combined carbon and hydrogen content of wood pellets places them in position between lower grade fuels such as solid waste and higher grade fuels such as bituminous coal. Pellets can be produced which have an energy density about 57 percent that of bituminous coal.

Capital cost of a wood pellet production plant receiving between 120 and 385 tons/day (108 and 347 MT/day) hogged wood or wood chips ranges up to approximately $3380/ton/day ($3715/MT/day) input. Wood pellets can be produced for between $17.00 and $18.00/ton ($18.89 and $20.00/MT), neglecting cost of raw material, amortization, taxes, insurance, and depreciation. Electrical power is a highly significant annual cost influencing the as-produced cost of pellets, and accounting for up to 46 percent of total annual production costs. Wood pellet production cost is also strongly influenced by the delivered cost of raw material feedstock. Because of increasing local demand for hogged wood and wood chips, the current cost of about $6.00/ton ($6.67/MT) could rise to $12.00/ton ($13.33/MT) or more. Such increases would mean that the cost of raw materials at the plant on an

annual basis easily could be greater than all other annual costs associated with the operation and maintenance of a wood pelleting plant.

4 HANDLING, STORING, AND FEEDING

General

Technology for handling, storing, and feeding relatively low energy density fuels — such as wood chips and pellets — limits the scale at which those fuels can be used. This is principally because of the large amount of wood material which must be handled; in other words, although the handling of wood fuel is similar to that of coal in other respects, the volume of wood required can be as much as 10 times that of coal.[28]

Three key areas of material handling confront the planner and designer when considering installation-scale production and use of wood pellets:

[28] Wood Energy for Small-Scale Power Production in North Carolina (Ultrasystems, Inc., 1978).

Table 9

General Material Properties Affecting Handling

Property/Characteristics	Wood Bark	Hogged Wood	Wood Shavings	Wood Pellets	Illinois Bitum. Coal (Run of Mine)	Fly Ash
Size						
Very fine – minus 100 mesh (0.150mm)						
Fine – 100 mesh to ⅛ in. (0.150 to 3.175 mm)						X
Granular – ⅛ to ½ in. (3.175 to 12.7 mm)						
Lumpy – lumps ½ in. and over (12.7 mm)				X	X	
Irregular – fibrous, stringy, etc.	X	X	X			
Flowability						
Very free flowing, repose up to 30°						X
Free flowing, repose 30° to 45°				X	X	
Sluggish, repose 45° and over	X	X	X			
Abrasiveness						
Nonabrasive		X	X	X	X	
Mildly abrasive	X					
Very abrasive						X
Special Characteristics						
Mildly corrosive					X	
Degradable		X	X		X	
Light, fluffy			X			
Interlocks or mats to resist digging	X	X	X			
Aerates and becomes fluid						X
Packs under pressure		X	X	X		
Deteriorates subject to free moisture				X		

1. Receipt of hogged wood or wood chips at the production site

2. Wood pellet storage and feeding at the heating or power plant

3. Performance of wood pellets in existing coal storage and handling equipment.

For an average Army central boiler, a storage vessel of approximately 250 tons (228 MT) capacity will hold enough wood pellets for 3 days (e.g., over a weekend) of operation. Fuel withdrawal rate will vary up to 3.5 tons/hour (3.2 MT/hr). On a volumetric basis, the static storage capacity required can be up to about 15,000 cu ft (425 m³) and withdrawal rates up to 200 cu ft/hr (57 m³/hr). A wood pellet production plant receiving about 120 tons/day (108 MT/day) wood chips must handle up to 16,000 cu ft (454 m³) of material at the beginning of the pellet production process. Fortunately, the volume-handling requirements for wood chips and pellets for an average installation-scale application are well within the capabilities of modern handling, storing, and feeding technology and might even be considered relatively small when compared to wood

fuel use[29] that would be required at a major utility – a municipal power company, for example.

Material properties determine both the design of a new system and the modifications to an existing system for handling, storage, and feeding.[30] Table 9 gives general information on the material properties of coal fly ash, Illinois bituminous coal, and a variety of forms of wood. Of particular interest in comparing wood pellets to coal are the sensitivity of pellets to free moisture and their tendency to pack somewhat under pressure; coal has neither characteristic. Generally, the flow property of pellets compares with that of coal; however, this characteristic depends partly on the fraction of fines and moisture in the material, and on the configuration and wall material of the storage vessel. The role of these factors in the design of a wood pellet storage vessel is discussed later.

[29]J. Johanson. "Design for Flexibility in Storage and Reclaim." *Chemical Engineering* (30 October 1978); *Supplemental Wood Fuel Experiment* (Board of Light and Power, Grand Haven, MI, 1978).

[30]*General Catalogue 900* (Link Belt Corp., 1950).

Receiving Raw Material for Wood Pellet Production

Hogged wood or wood chips can be delivered to a wood pelleting plant in several ways, but the material almost always is delivered by truck.[31] Normal tractor trailers are suitable for hauling, and unloading can be done by tilting the whole truck on a platform, or by using equipment designed on a portable conveyor belt principle to unload vans. Trucks with bottom gravity extraction—such as those for hauling grain—have also been used to deliver wood chips.

Normally, the material is dumped at a receiving area and handled by bobcat or front-end loader. Either type of mobile equipment is suitable for managing piles of wood, and for moving the material to the beginning of the wood pelleting process. For some time, such equipment has successfully handled wood chip quantities well over the average installation amount of 16,000 cu ft/day (454 m³/day). Other reclaim technologies such as bottom-tunnel, bucket-wheel, and scraper truck have been successfully used on bulk solids in the chemical process industries.[32] Front-end loaders are preferred for managing materials stored in volumes up to 20,000 cu ft (566 m³), are not hindered by the material's tendency to arch and/or rathole, and have good potential for remixing segregated solids, but generally provide only poor uniformity of discharge. While bottom-tunnel and bucket-wheel reclaim methods provide better uniformity of discharge, they are sensitive to the arching tendency of the material and (because of economics) are generally preferred for large applications (700,000 cu ft [19 824 m³] of material and more). The scraper truck, which has remixing and discharge uniformity characteristics similar to those of the front-end loader and is not limited by the material's tendencies to arch and/or rathole, is used most often in larger systems.

Depending on plant size, a number of techniques can be employed for storing wood; these include bin storage, open storage in piles, and shed storage. Because a plant often stores a large volume of wood material, which is sensitive to precipitation, the wood is replenished regularly and usually does not remain in storage for more than 14 days. It is noteworthy that problems still exist with residual decomposition

and spontaneous combustion during medium- and long-term storage.[33]

One concept for a low-cost covered storage area which appears highly promising was recently created by Ultrasystems, Inc., and is shown in Figure 6.[34] The structure shown is an A-frame, shop-fabricated steel building with 7200 sq ft (669 m²) floor area for enclosed storage of about 1000 tons (910 MT) of chips, hogged wood, or sawdust. Material is fed to the building by a screw conveyor near the roof and distributed the length of the building. Material is reclaimed by screw conveyors moving back and forth under the pile at floor level, discharging into conveyors at the center of the building and moving from these to a processing plant. While not yet built, this structure appears to have good potential application in areas where outdoor wood storage is infeasible.

Wood Pellet Storage Vessel Design

A storage vessel (bin and feeder) with approximately 250 tons (228 MT) or 15,000 cu ft (425 m³) capacity can support 3 days of full-load operation for an average Army central boiler. Because wood pellets tend to break apart when exposed to rainfall, storage must be enclosed. Design of the optimum bin and feeder system is determined by the properties of the material to be stored. While the design presented here is intended for use as wood pellet storage at an Army heating or power plant, it equally applies to temporary storage of wood pellets at their production site.

Numerous vessels exist for storing bulk solids such as wood pellets, and they include multiple-outlet silos, single-outlet bins and portable bins. For each configuration, design may be either for mass flow or funnel flow, depending on the nature of the material and active storage volume requirements. Mass flow designs handle materials on a first-in, first-out basis and therefore are recommended for materials which degrade over short to moderate periods of time. Mass flow designs have excellent potential for remixing segregated solids, provide uniform discharge, are not limited by ratholing, and have long-proven applications to the storage and feeding of solids such as wood pellets. Typical coal bunkers at Army heating

[31]*Considerations in Selecting Wood as an Immediate Source of Reliable and Economical Energy for Military Installations*, FESA-TS-2061 ADA 071791 (U.S. Army Facilities Engineering Support Agency, 1978).

[32]J. Johanson, "Design for Flexibility in Storage and Reclaim," *Chemical Engineering* (30 October 1978).

[33]*Wood Energy for Small-Scale Power Production in North Carolina* (Ultrasystems, Inc., 1978).

[34]Personal communication with Mr. C. Vail, Ultrasystems, Inc., McLean, VA, 7 August 1979.

BUCKET CONVEYOR

SCREW CONVEYOR
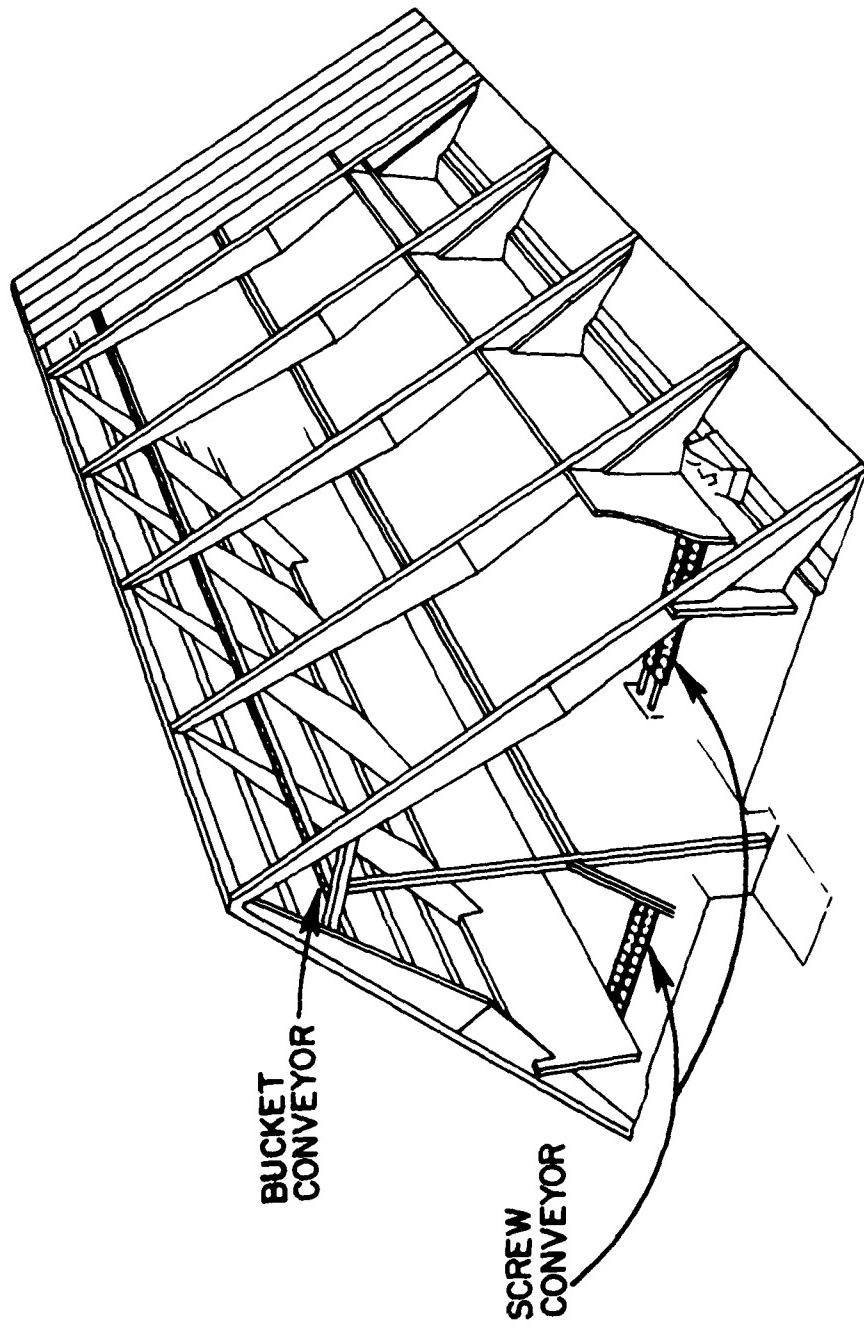
Figure 6. Wood chip storage concept.
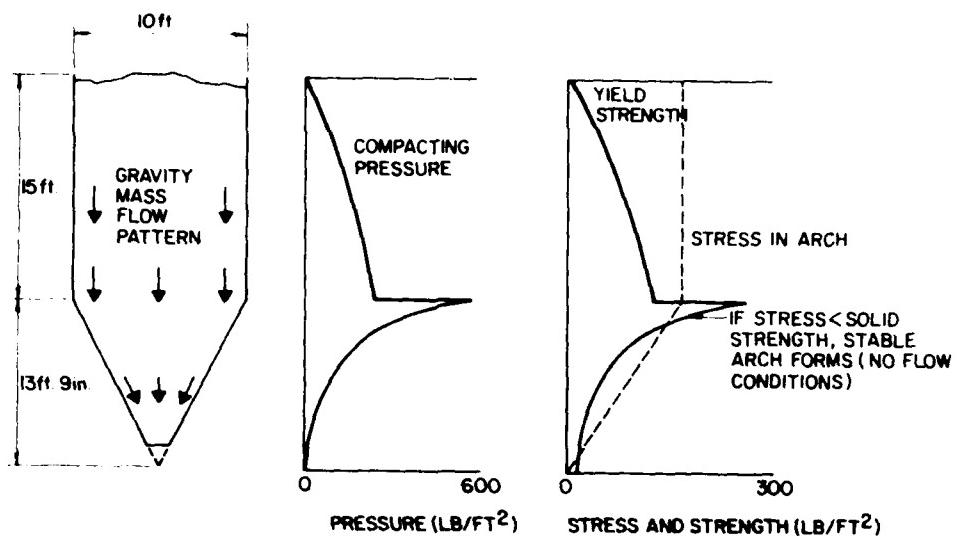
Figure 7. Flow/no-flow conditions in gravity mass flow vessel.

and power plants are designed for mass flow of the fuel.

When designing a storage vessel, it is important to remember that the consolidating pressure acting to compact the material stored in the vessel varies with position in the vessel (Figure 7). For each position in the vessel, there is a corresponding consolidating pressure (σ) and a measured strength of the solid (f). If the strength is great enough to support an arch, then an arch will form. In a typical conical-type vessel, the consolidating pressure is greatest at the transition from the vertical-walled bin to the hopper section which slopes inward to the vessel outlet. Pressures in this region can be as high as 600 lb/cu ft (9612 kg/m³), contrasted to values up to 200 lb/cu ft (3204 kg/m³) encountered elsewhere in the vessel. It is in this region that the strength of t e solid is greatest.

It has been demonstrated that the stress in a stable, self-supporting arch is proportional to span width.[35] If the stress in the arch exceeds the strength of the solid, the arch will not form, and flow will occur.

The two most important physical conditions bearing upon solid flow are moisture content and consolidating pressure. Table 10 lists the basic flow properties of solids and describes how those properties change with respect to the variables of moisture and pressure. Comprehensive treatment of these properties can be

found elsewhere and is not repeated here.[36] In general, however, probability of mass flow is reduced with increasing moisture content. And with increasing consolidating pressure (as an element of solid approaches the hopper transition), the unconfined yield strength increases significantly, further impeding mass flow.

The basic bulk flow properties of virtually any solid can be determined by laboratory analyses applying state-of-the-art procedures and apparatus. As part of this investigation, CERL requested Jenike and Johanson, Inc., to conduct such analyses of wood pellets produced by Tennessee Woodex, Inc., and to recommend a bin and feeder system suitable for use at an average Army central heating and power plant. Figures 8 and 9 depict the storage and feeding apparatus respectively. Appendix A presents details on the bin and feeder design, and Appendix B provides data from the laboratory analyses of the wood pellets. Such a system can be used independently of an existing coal bunker. If the system is used independently, wood pellets could be fed to a transition hopper located above the feeder of the boiler which is to fire wood pellets.

Use of Wood Pellets in Existing Coal Bunkers

The economics of using wood pellets as a substitute or supplementary heating or power plant fuel depends upon the capability of existing coal-designed equipment to reliably accommodate the new fuel. The total implementation cost of using wood pellets can be

[35] J. Johanson, "Know Your Material—How to Predict and Use the Properties of Bulk Solids," *Chemical Engineering*, Vol 85, No. 24 (30 October 1978).

[36] A. Jenike, *Storage and Flow of Solids*, Engineering Experiment Station Bulletin 123 (University of Utah, 1970).

total volume = 18,000 cu.ft.
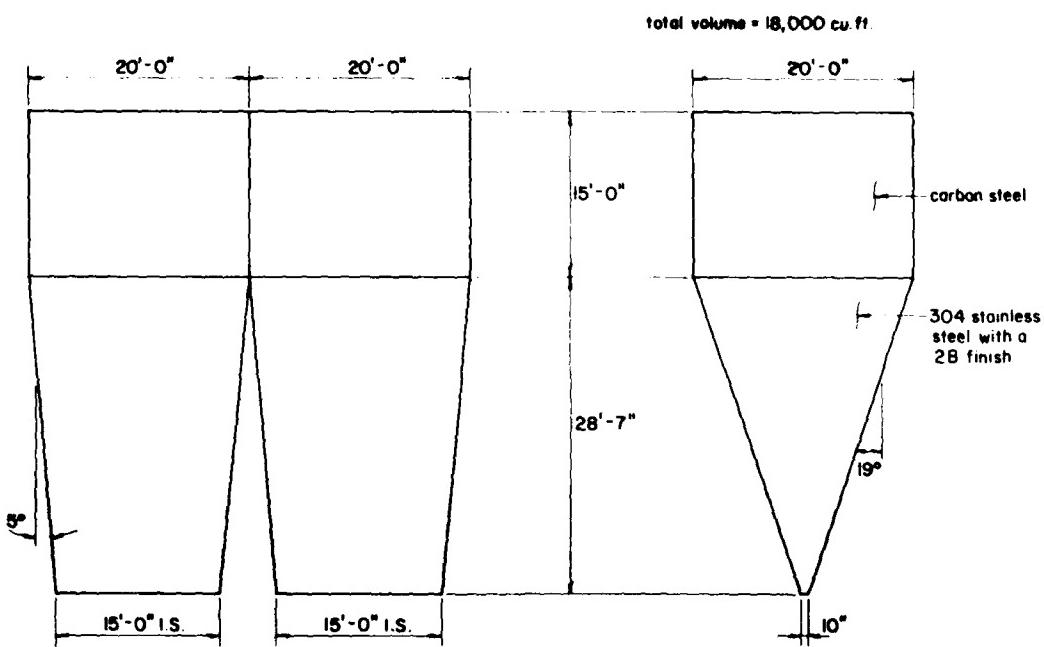
Figure 8. Wood pellet storage bin.
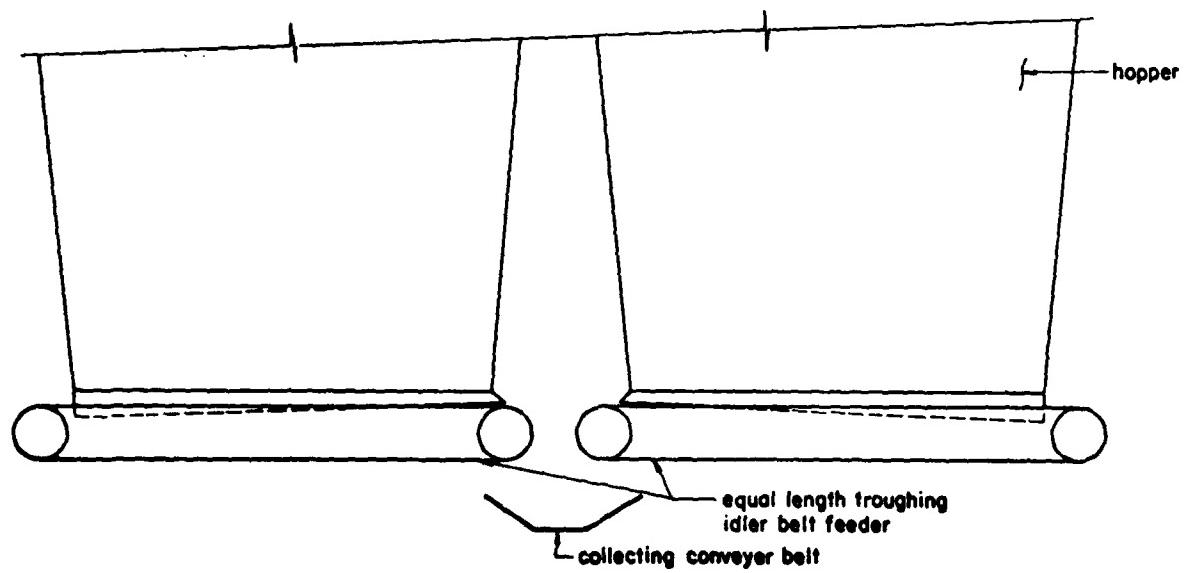
Figure 9. Wood pellet feeding apparatus.

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reduced if inplace coal bunks can be used for pellet storage. In other words, if new pellet storage facilities do not have to be built, this could mean a savings of as much as $300,000, depending on capacity and site-specific conditions.

It is premature to generalize whether all existing Army coal bunkers can reliably store and feed wood pellets, because no comprehensive inventory exists by which the design basis and configuration of such equipment can be definitely identified. In addition, nearly all existing coal bunkers were designed and installed well before the mid-1950s, when the modern basis of bin and feeder design was quantitatively formulated and unified by Jenike at the University of Utah.[37] Up to that time, bunker design relied heavily on successful precedent, experience, and intuition, and was not as strongly linked to bulk-solid properties as it is today.

Although the potential for all Army coal bunkers to reliably handle wood pellets cannot be defined, a design for a new storage facility (e.g., Figures 8 and 9) and an analysis of wood pellet properties can be used as a baseline against which to compare a specific existing bunker and make some general determinations about whether it must be modified to handle the new material. But modifying an existing coal bunker to accommodate wood pellets may considerably diminish its ability to reliably accommodate coal. It is not yet possible to extrapolate the behavior of one material in order to anticipate the behavior of another material having similar chemical composition; nor is it possible to expect a design for one material to be completely workable for a different material.[38]

Nonetheless, one approach to establishing bunker modification criteria can be made by referring to Figures 3 and 8, the former being the coal bunker at Fort Benjamin Harrison, IN, which provided short-term storage for wood pellets during a test, and the latter being an optimal design for a new bin to store wood pellets. During the Fort Benjamin Harrison wood pellet test, about 40 tons (36 MT) of Woodex was stored in a section of the bunker reserved for the pellets. Although the Woodex remained in the bin

[37]A. Jenike, *Flow of Solids in Bulk Handling Systems/Flow of Bulk Solids in Bins*, Engineering Experiment Station Bulletin 64 (University of Utah, 1954).

[38]J. Johanson, "Know Your Material—How to Predict and Use the Properties of Bulk Solids," *Chemical Engineering* (30 October 1978).

fewer than 3 days, significant ratholing was observed, along with the tendency of fines to adhere to the lower reaches of the parabolic bunker wall.

These phenomena can be explained—at least generally—by the basic properties listed in Table 10. Since the strength of the solid is directly proportional to the pressure acting on it and inversely proportional to free flow, it is important to note that the peak pressures (hence strength) occur at the hopper transition point. The peak pressure (n_t) for a cylindrical vessel is given by:

$$n_t = n_{tr} + \frac{3.3\left[\frac{Q_c}{A_c} - \left(\frac{4}{\pi}\right) q \, \gamma D\right]}{(2 - 0.4 \sin \theta')M \, (\sin \theta' + \cos \theta' \tan \phi')} \quad [Eq 1]$$

where Q_c = total vertical force within solid at transition due to stressed in the cylindrical vessel

A_c = area of horizontal vessel section

q = nondimensional vertical force acting within the solid at the transition due to radial stresses

γ = bulk density of the solid

D = diameter of cylindrical vessel (or width of rectangular or square vessel)

θ' = slope of hopper wall with respect to vertical

M = coefficient (1 for conical, 0 for wedge hoppers)

ϕ' = solid-wall kinematic friction angle

N_{tr} = radial wall pressure at hopper transition.

Note that the transition radial pressure is given as:

$$n_{tr} = S(M, \delta, \theta', \phi') \frac{1 - \sin \gamma \cos 2\psi'(\gamma, \phi')}{2 \sin \theta'} \gamma D \quad [Eq 2]$$

where S = major stress at vessel wall

γ = effective angle of internal friction of the solid

ψ' = a functional expression of δ and ϕ'.

$$\frac{Q_c}{A_c} = \frac{\gamma R}{\mu k} (1 - e^{-MK\frac{H}{R}}) \quad [Eq 3]$$

where R = hydraulic radius

μ = solid-wall coefficient of friction

K = ratio of horizontal to vertical pressure (Janssen Factor)

H = height of cylinder.

Table 10

Basic Bulk Flow Properties of Solids

(Modified from A. Jenike, *Storage and Flow of Solids*, Engineering
Experiment Station Bulletin 123 (University of Utah, 1970).)

Property	Symbol (Units)	Description	Change With Increased Moisture	Change With Increased Consolidating Pressure (w)
Effective Angle of Internal Friction	δ (deg.)	Kinematic friction condition during steady flow	Usually increases	Significant decrease at low consolidating pressures
Angle of Internal Friction	ϕ (deg.)	Friction condition as bulk solid slides on itself at onset of flow	Usually decreases	Usually increases
Kinematic Angle of Surface Friction	ϕ' (deg.)	Coefficient of kinematic friction between solid and wall surface is Tan ϕ'	Can increase or decrease	Slightly decreases
Bulk Density	γ (lb/cu ft)	Unit weight of bulk solid	Usually decreases at low consolidating pressures	Increases
Unconfined Yield Strength	f (lb/ft²)	Cohesion and agglomerating tendency of solid, expressed as function of consolidating pressure	Increases significantly up to saturation	Increases significantly
Compressibility Factor	β	Slope of log a vs log s	Increases	Little change. Tends to zero at very high and very low pressures
Permeability	k (ft/sec)	Superficial flow velocity of air through the solid, with a gas pressure gradient equal to a	Increases up to saturation	Significant decrease

Values for factors in Equations 1 through 3 and procedures for obtaining them for specific solids are rather well established and published elsewhere.[39]

In this analysis, it is enough to recognize the essential relationships among the variables in Equations 1 through 3. Variables relating parameters of an existing storage vessel (e.g., height, diameter, cross-sectional area, etc.) will mutually cancel when the performance of coal is compared to that of wood pellets, and only those variables pertaining to solid properties will play a role in revealing whether pellets will perform in a coal-designed system. The solid properties of interest are bulk density (γ), solid-wall kinematic angle of friction (ϕ'), effective angle of internal friction (δ), and the solid-wall coefficient of friction (μ).

The major observable difference in flow properties of coal and Woodex during the Fort Benjamin Harrison test appeared to be related to the wood's frictional characteristics, and this, in turn, was attributed to the relatively high fines content of the Woodex. The flowability of any solid containing both fine and coarse particles is governed by the properties of the fines fraction.[40] This is because shearing takes place across the fines during flow, with coarse particles being essentially passive agents. The size of the coarse particles will affect the tendency of material to interlock at the hopper outlet. A high-fines fuel has greater surface area per unit volume, generally with a proportional increase in internal friction and frictional

[39]A. Jenike, *Storage and Flow of Solids*, Engineering Experiment Station Bulletin 132 (University of Utah, 1970).

[40]A. Jenike, *Storage and Flow of Solids*.

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resistance at the wall. The friction is further increased by the relatively fibrous nature of Woodex fines compared to coal fines; fibrous particles tend to interlock, further increasing the internal friction angle of the solid, and thereby its strength and the probability of flow problems.

During the Fort Benjamin Harrison Woodex test, ratholes formed in the wood pellets above the hopper outlet essentially because the hopper walls were not steep enough to cause the material to flow down them. A rathole will be stable when the stress in its walls is less than the strength of the solid, and when the stress exceeds the solid's strength, the rathole will fail and flow will occur. At Fort Benjamin Harrison, the rathole occurred in a region extending upward about 10 ft (3.1 m) from the 2.5 ft by 2.5 ft (0.8 by 0.8 m) hopper outlet. Were the outlet larger, the flow channel would have been proportionally greater, the stress in the rathole would have been larger, and the position at which the rathole was unstable would have been lower. Since the stress in the solid is proportional to the diameter of the rathole, enlarging the hopper outlet to a point where stress exceeds the solid strength would have allowed good flow. Moreover, rathole obstructions to gravity mass flow will not form when hopper slopes are steep and smooth enough to cause flow along them. Mass flow design is hence a function of the solid-wall friction angle (ϕ')[41] Therefore, a second modification for wood pellet storage at Fort Benjamin Harrison would involve increasing the slope and eliminating the curvature of the parabolic bunker, either by reconstruction or by placing inserts in it.

A limiting relationship thus exists between the friction angle (ϕ') and the conical half angle of the hopper, as measured from the vertical. Since the friction angle varies with normal pressure on the solid, that angle's position changes within the hopper. The limiting relationship between the friction angle and the half angle of the hopper is functionally related to the effective internal friction angle (σ) of the solid. For solids such as the Woodex tested at Fort Benjamin Harrison (multiple sieve sizes, high in fines) where the internal friction angle can be relatively great compared to coal, the critical hopper angle will decrease (to approach 0°, or vertical) linearly with increasing

[41]J. Johanson, "Know Your Material—How to Predict and Use the Properties of Bulk Solids," *Chemical Engineering* (30 October 1978)

surface friction angle. Specific hopper angles and friction angles must be determined with respect to the effective angle of the solid's internal friction; that friction itself can be identified for virtually any bulk solid using state-of-the-art laboratory techniques.

Such techniques must also be applied to ascertain time-related changes of solid properties—changes such as moisture migration and temperature increase. (It is expected that changes due to chemical reaction and deaeration will be virtually nonexistent with wood pellets.) Changes in moisture content can be caused by factors such as contamination of the fuel by rainfall, the hydroscopicity of the fuel, and the corresponding rate at which it picks up water from ambient atmosphere. Even subtle changes in moisture content can significantly affect the frictional properties of the solid. Temperature effects can include freezing of moisture in the material (resulting in ice bonding) and overheating. There is no evidence that wood pellets will give off heat during moderate-term storage, as does refuse-derived fuel (in large part due to biodegradation). With the exception of freezing possibilities, there is no evidence that temperature will significantly affect use of wood pellets. Normally, time-related effects on the flowability of a solid are simulated in the laboratory and directly influence the design and/or modification of storage equipment.

A significant factor affecting solid flow properties is overpressure. In normal handling, wood pellets are subjected to vibration, impact, and external loading. These actions add to the total compacting pressure to which the material is subjected. Traditional flowability analyses consider only gravitational forces from the weight of the material. If overpressure does not compound the effect of gravity, there is no change in critical storage vessel dimensions. Increased compaction, however, can significantly increase the tendency of some solids to arch in a hopper. In DOD wood pellet tests, the pellets were subjected to a variety of overpressure forces between the time they were produced and the time they were fired. At Fort Benjamin Harrison, it was observed that a significant fraction of the delivered pellets lost their structural integrity because of high shear forces at the point where the fuel-receiving hopper discharged by gravity to an elevating transition conveyor. The net result was an increased fraction of fines in the material

which was delivered to the bunker. With wood pellets, these conditions cumulatively led to increased solid strength and doubtlessly contributed to the tendency of the material to rathole in the bunker; coal, however, is affected insignificantly during normal operation at Fort Benjamin Harrison.

Hence, at any location considered for wood pellet use, it is not enough to know only the material properties of pellets on an as-produced basis in order to project how well they can be stored and handled in an existing bunker. Rather, the design and/or modification of a storage facility must consider the changes in the properties of the bulk pellets as they pass from their site of production to the point they enter the boiler. Because of the site-specific nature of fuel systems Army-wide, only general guidelines can be offered for the reliable handling and storage of wood pellets; and their use—whether as a substitute fuel or mixed in some proportion with coal—must be determined on a case-by-case basis.

Summary

Although handling and storage technology limits the scale at which wood can be used as a fuel, it is evident that potential installation-scale wood pellet systems are small enough to be free of such restrictions. Conventional, long-proven technology exists for handling and storing hogged wood and wood chips at the scale at which an average installation will use them. Where required, advanced concepts for enclosed storage of such materials appear to be technically feasible but will add to the cost of producing and/or using wood pellets.

The design of a bin and feeder system to reliably accommodate wood pellets in quantities appropriate for installation-scale use is achievable using state-of-the-art techniques and procedures to determine and apply critical properties of bulk materials. Such techniques and procedures should also be applied to determine on a case-by-case basis whether existing coal storage equipment can be used either unchanged, or with modification, to accommodate pellets. The essential, design-related properties of wood pellets can be determined and appear to be different from those of most coals. Nevertheless, there is every reason to believe that through application of modern engineering principles and practices a reliable wood pellet handling, storage, and feeding system (either a new vessel or a modified existing bunker) can be designed and constructed for installation-scale use.

5 COMBUSTION

General

As in the case of handling, storage, and feeding equipment, the capability of an existing boiler to fire substitute or supplemental wood pellets partially determines the cost-effectiveness of their use. In the ideal case, wood pellets could completely substitute for coal with no modifications to or changes in performance of the combustion hardware. Such has not been entirely the case in experience with wood pellets to date, but their performance has been far from unsatisfactory as a substitute in boilers designed for coal. In this chapter, some of the major factors limiting wood pellet use in existing boilers are discussed.

Fuel Composition and Characteristics

As indicated earlier in Table 6, wood and wood products are highly oxygenated fuels with about two-thirds the energy content of coal; softwoods generally contain more energy than hardwoods (dry weight basis) because of higher lignin (therefore carbon) content and the presence of more resins in the extractions. Wood is a composite of three basic polymers: cellulose $(C_6H_5O_{10})$, lignin $(C_9H_{10}O_3 (OCH_3)_{0.9-1.7})$, and hemicelluloses such as xylan $(C_5H_8O_4)$. There are usually only minor quantities of extractives and minerals (ash). Most hydrocarbon fuels, including coal, are parafinic and can be represented by the general formula $(CH_2)_n$; an appropriate similar representation for wood is $CH_n(H_2O)_m$. In general, hardwoods contain by weight about 43 percent cellulose, 22 percent lignin and 35 percent hemicelluloses (extractive-free basis), while softwoods contain equal cellulose, 29 percent lignin and 28 percent hemicellulose. In general, the heating value of the fuel increases in direct proportion to its lignin content.[42]

The relation of solid fuel properties to their combustion performance for several firing methods is shown in Table 11.[43] Such information must be considered when evaluating an alternate fuel for an existing heating or power plant. For traveling-grate (overfeed) and spreader-stoker applications, the rela-

[42]D. Tillman, *Wood as an Energy Resource* (Academic Press, 1978).

[43]S. A. Hathaway and R. J. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Interim Report E-110 ADA042578 (CERL, July 1977).

Table 11

Combustion Performance Table for Solid Fuel Properties

(From S. A. Hathaway and R. J. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Interim Report E-110 ADA042578 [CERL, July 1977].)

Solid Fuel Property	Solid Fuel Firing Method			
	Underfed Single Retort	Underfed Multiple Retort	Traveling Grate	Spreader Stoker
As-Fired Size Consistency	1*	2	2	1
Moisture	3	3	4	3
Caking Index	2	2	1	3
Ash Fusibility	2	2	3	3
Grindability	4	4	4	4
Friability	3	3	3	3
Volatile Matter	3	3	3	3
Fixed Carbon	4	4	4	4
Ash Content	3	3	2	3
Heating Value	4	4	4	4
Ash Viscosity	3	3	3	3
Ash Composition		**		
Sulfur		***		
Chlorides		***		

*1 = Very Important
2 = Important
3 = Minor Importance
4 = *Little Importance*
**Affects fireside fouling; not important to combustion.
***Important from corrosion standpoint, not vital to combustion.

tively more important tabulated properties are consistency of as-fired size, caking index, and ash content. Observations during wood pellet tests indicated that wood pellets have a negligible tendency to cake. The low ash content of wood pellets is good from the standpoint of boiler heat loss, pollution potential, waste disposal, and equipment wear, but may be a somewhat negative factor insofar as ash bed protection of grate materials from furnace heat is concerned. Size consistency is highly important in both types of firing systems. Combustible fines can sift through a chain grate, resulting in fuel loss and reduced fuel efficiency overall. In spreader stokers, fines can readily entrain into combustion gases and increase the stack gas particulate density. Moreover, the trajectories of fines present a problem in mechanical feeders; they are vastly lighter than whole pellets and make feeder settings quite difficult to adjust for correct grate coverage.

To some extent, the size of the wood pellets is controllable during production. However, between production and firing, wood pellets are subject to a variety of overpressure effects which cumulatively lead to increased fines content in the material at the boiler. A final screening stage before firing is one way to reduce the fraction of fines entering the boiler, but will add to the costs of implementing a system to use wood pellets. Moreover, if the fines fraction is large, a similarly large fraction of fuel will be lost by their separation from the more appropriate pellets before firing. They can, of course, be repelleted or sent to the furnace through the fly ash reinjection system if one exists.

Feeding

In all DOD wood pellet tests, feeding the fuel to the furnace has been a critical consideration and has required operating adjustments. A stoker's capability to feed increased masses of material to the furnace is an important limiting factor when using substitute wood pellets. It is perhaps more important in overfeed traveling chain grate stokers than in spreader stokers, because the feed rate is governed largely by the rate at which the continuous grate travels to the rear of the furnace.

Table 12
Calculation of Stoker Speed for Coal

(From *Combustion Engineering* (Combustion Engineering Corp., 1966).)

Basic Design Information

Maximum Continuous Rating (MCR)	115,000 lb/hr (52 200 kg/hr)
Enthalpy of 125 psig Saturated Steam	1,193 Btu/lb (2772 kJ/kg)
Enthalpy of 220° Feedwater	188 Btu/lb (437 kJ/kg)
Heat Added per Pound	1,005 Btu/lb (2335 kJ/kg)
Total Heat Added	115.6 x 10⁶ Btu/hr (1.220 x 10⁹ kJ/hr)
Estimated Boiler Efficiency	76.5 percent
Total Heat Fired	151.0 x 10⁶ Btu/hr (1.593 x 10⁹ kJ/hr)
Fuel Fired (11,350 Btu/lb Coal)	13,300 lb/hr (6040 kg/hr)
MCR Stoker Heat Release	500,000-550,000 Btu/sq ft/hr
	(5 700 000-6 200 000 kJ/m²/hr)
MCR Allowable Grate Speed	30-45 ft/hr (9-14m/hr)
Fuel Bed Depth	6 in. (15 cm)
Fuel Density	50 lb/cu ft (802 kg/m³)

Stoker Speed

Stoker Area = 151 x 10⁶/525,000	288 sq ft (26.8 m²)
(1.593 x 10⁹/5 950 000)	
Actual Stoker Area = (15 ft wide x 19 ft 6 in. long)	292 sq ft (27.1 m²)
(4.6 m x 5.9 m)	
Volume of Coal Fired = 13,300/50 (6040/802)	266 cu ft/hr (7.53 m³/hr)
Stoker Speed = 266 cu ft/hr (7.53 m³/hr)	35.5 ft/hr (10.8 m/hr)
½ ft Bed x 15 ft width	
(0.15 m x 4.57 m)	
Stoker Heat Release = 151 x 10⁶/292	517,000 Btu/hr/sq ft
(1.593 x 10⁹/27.1)	(5 880 000 kJ/hr/m²)

Table 12 presents a published computation of stoker speed for coal in a boiler rated 115,000 lb/hour (52 163 kg/hr) MCR.[44] While this capacity is somewhat large compared to a typical Army central boiler, the illustration here applies equally to larger and smaller boilers. The boiler has a grate speed of 35.5 ft/hr (10.8 m/hr) at MCR with an allowable maximum of 45 ft/hr (13.7 m/hr). Assume wood pellets—which have a heating value of 8350 Btu/lb (19 417 kJ/kg) and a density of 35 lb/cu ft (560 kg/m³)—were substituted for coal. Stoker speed is a function partly of volume of fuel fired, fuel bed thickness, and stoker width, and can be expressed by the following equation:

$$V_s = \frac{(\Delta H)\ (SR)}{(\eta)(HV)(\gamma)\ (W_s)(B)} \quad [Eq\ 4]$$

where V_s = stoker velocity (ft/hr) (m/hr)

[44]*Combustion Engineering* (Combustion Engineering Corp., 1966).

SR = steaming rate (lb/hr) (kg/hr)

η = fractional efficiency

HV = heating value of fuel (Btu/lb) (kJ/kg)

W_s = width of stoker (ft) (m)

B = bed depth (ft) (m)

ΔH = enthalpy added per pound steam (Btu/lb) (kJ/kg)

γ = fuel density (lb/cu ft³) (kg/m³)

For the coal on which the analysis in Table 12 was conducted, where SP = MCR, the calculated stoker velocity is 35.5 ft/hr (10.8 m/hr). For wood pellets, letting all variables but HV and γ remain the same, the calculated stoker velocity is

$$[Eq\ 5]$$

$$V_s = \frac{(1005)\ (115,000)}{(0.765)\ (8350)\ (35)\ (15)\ (0.5)} = 68.9\ ft/hr\ (21.0\ m/hr)$$

This is approximately 53 percent greater than the allowable maximum travel rate under the design conditions stated for coal. Since the grate travel speed in traveling grate stokers essentially represents the fuel feed rate, it is clear that it is a limiting factor governing the maximum load at which a boiler can operate continuously when using substitute wood pellets.

The extent of derating can be estimated by rearranging Equation 4 to solve for SR with $V_s = 35.5$ (Table 12), and letting the fuel energy density (ED) = (HV) (γ). Then

$$SR = \frac{(\gamma)\,(ED)\,(W_s)\,(B)\,(V_s)}{\Delta H} \qquad [Eq\ 6]$$

For wood pellets, SR = 59 230 lb/hr (26 866 kg/hr), representing a derating of about 48.5 percent.

One way of reducing the derating is to increase the fuel bed depth (B) and increase the rate of fuel feed (as represented here by grate travel rate [V_s]) to its maximum. Letting $V_s = 45$ ft/hr (13.7 m/hr) and B = 0.67 ft (203 mm), about the maximum bed depth allowable in most systems, Equation 6 reveals an MCR of 100,607 lb/hr (45 635 kg/hr), representing a derating of about 12.5 percent. This analysis presumes that there will be no loss in efficiency (η) when using substitute wood pellets, while test experience to date indicates efficiency drops of up to 10 percent at least. Letting $\eta = 0.665$ and solving Equation 6 for SR = MCR, a value of 87,456 lb/hr (39 669 kg/hr) is computed, representing a derating of about 24 percent.

Similar analyses can be performed to determine feeder turnup rates for spreader stokers, and similar conclusions can be reached. It is important to note that the extent of derating depends on factors such as changes in boiler radiative and convective heat transfer rates, as well as on feed-related phenomena. In this analysis, it is clear that the extent of derating is dependent on how far the boiler is pushed with respect to its maximum operating conditions. The closer to these conditions it is continuously operated, the less flexibility it has to adjust to problems such as fluctuations in fuel quality.

In addition, the extent of derating is directly proportional to the type of fuel. As noted previously, the energy density of wood pellets is higher than that of wood chips and hogged wood, but still only about 57 percent that of coal. Hence, the effectiveness by which existing coal-designed boilers can use wood pellets is inescapably linked to the production technology used to dry and compact wood into a substitute fuel.

Reactivity

When a solid fuel such as coal or wood is fed to a furnace, a process involving several steps begins. First, the material dries (evaporation of moisture, which represents a heat loss in the system). This is followed by volatilization, ignition of volatiles, free combustion, and char burnout. For a given piece of fuel, the steps sometimes can be considered as separate stages; but in any given area of the furnace containing a significant mass of fuel, all steps may be taking place simultaneously.

The rate at which wood pellets might be expected to burn is very generally indicated by the fuel chemistry data shown in Table 6. Wood pellets are substantially higher in volatile matter than coal, and contain far less fixed carbon per unit weight. One would expect, therefore, that overall combustion of the pellets would emphasize gas-phase combustion of volatiles, while that of coal would place less emphasis on volatiles and somewhat more on fixed carbon combustion and burnout stages. In wood, the content of cellulose and hemicellulose principally promotes the release of volatiles, while lignin, which also releases volatiles, primarily promotes char formation. Lignin content ranges between 18 and 33 percent by weight, while cellulosic materials account for 65 to 70 percent of the total mass.[45]

Several studies have reported that the combustion properties of wood and wood pellets are significantly different from those of most coals. Kochler reported in 1924 that air-dried wood (with 12 to 15 percent moisture, similar to wood-pellet material) required less than 1-minute residence time before ignition in thermal environments not unlike those prevailing in boilers (707°F [375°C] and greater).[46] More recently, Shafizadeh and DeGroot showed that the energy required to obtain ignition of dry cellulose at 575°F (302°C) is about 225 Btu/lb (523 kJ/kg), and the net heat release is about 5070 Btu/lb (11 970 kJ/kg). For cellulose containing 50 percent by weight moisture at 600°F (316°C) the respective values are about 1450

[45]D. Tillman, *Wood as an Energy Resource* (Academic Press, 1978).

[46]A. Koehler, *The Properties and Uses of Wood* (McGraw Hill, 1924).

Btu/lb (3372 kJ/kg) energy input for ignition and about 3070 Btu/lb (7139 kJ/kg) net heat release.[47] Studies by the Army and the Pittsburgh Energy Research Center clearly indicated that highly cellulosic fuel materials—such as wood, paper and refuse-derived fuel—volatilized and ignited in typical furnace thermal environments up to 12 times more rapidly than bituminous coal, and that the temperature required for coal ignition at a given furnace residence time was about 302°F (150°C) greater than that required for ignition of the cellulosic fuels.[48]

Based on these studies, it appears that the rate of wood pellet volatilization and ignition can be a significant limiting factor governing the feasibility of pellet use as a substitute boiler fuel, particularly where feeding is concerned. It was demonstrated earlier in this report through relatively coarse analysis that, based on overall stoker heat release requirements, some boiler derating will occur when using substitute wood pellets because of the large mass flow rate of fuel required (p. 42). Because the wood pellet's rate of consumption may be far more rapid than that of coal, the required fuel mass flow rate may be even greater, with proportional sacrifice of boiler load. Furthermore, since cellulosic materials require lower overall ignition and combustion temperatures than coal, there will be an attendant change in mean furnace temperatures with possible shifts in relative duty between radiant and convective heat transfer sections. Such a shift was recorded during the Woodex test at Fort Benjamin Harrison as reported earlier in this report, with suspected corresponding loss in overall efficiency.

It is important to understand that any boiler performance changes to be expected with wood pellets depend on the design of the boiler. Some boilers may have been designed for a highly volatile, highly reactive coal, in which case rating sacrifices when using substitute wood pellets may not be large. Units designed for a less reactive fuel must be carefully

[47]F. Shafizadeh and W. DeGroot, "Thermal Analysis of Forest Fuels," *Fuels and Energy from Renewable Resources* (Academic Press, 1977).

[48]*Reactivity and Gasification Characteristics of Low Ranking Coals and Potentially Reducing Waste Materials*, PERC/RI-76/2 (Pittsburgh Energy Research Center Report, 1976); S. A. Hathaway and J. S. Lin, "Combustion Rates of RDF," *Proceedings of Third International Conference on Environmental Problems in the Extractive Industries* (Wright Corp., Dayton, OH, 1977); S. A. Hathaway and J. S. Lin, *Thermogravimetric Analysis of Solid Refuse-Derived Fuels and Coal*, Technical Report E-149/ADA067829 (CERL, March 1979).

evaluated with respect to their potential performance when firing wood pellets, since their configurations may not be conducive to affordable wood pellet use.

Combustion Stoichiometry

The highly oxygenated character of wood pellets compared to coal is illustrated in the ultimate analysis presented in Table 13. While the pellets have about 38 percent oxygen by weight, the example coal has only 6.2 percent, or approximately 17 percent as much.[49]

The high oxygen content of this fuel, combined with the lower mass fractions of sulphur and nitrogen, has led to optimisim for substitute wood pellets. When substituting low-grade fuels in existing boilers, a common problem is the volumetric flow rate of the combustion products and the attendant effect increased gas velocities have on heat transfer and fan capabilities.[50] The data in Table 13 indicate that the combustion products from burning wood pellets are more than 40 percent less than from burning an equal mass of coal. Because wood pellets themselves contain a large fraction of the oxygen required for combustion, there is—compared to coal—correspondingly less combustion air which must be externally supplied. The low sulphur content of wood pellets allows more efficient use of oxygen in combustion because much more oxygen can be applied to oxidize the main fuel constituents of the material—carbon and hydrogen.

However, because of the relatively lower heating value of wood pellets, a greater mass of pellets than coal must be fed to the furnace to maintain a given heat release rate. For example, the data in Table 13 indicate that the coal mass flow rate to the boiler is 13,300 lb/hr (6033 kg/hr). To maintain an equivalent fuel heat release rate with pellets having a heating value of 8350 Btu/lb (19 417 kJ/kg) would require a pellet mass flow rate of 18,084 lb/hr (8203 kg/hr), which is approximately 1.36 times the coal mass flow rate. Using data from Table 13 as a general illustration, one finds that the mass flow rate of combustion products when firing coal at this rate would be 178,220 lb/hr (80 839 kg/hr) compared to 141,055 lb/hr (63 981 kg/hr) when firing wood pellets, using 25 percent excess air under both conditions. Theoretically, then,

[49]*Steam* (Babcock and Wilcox, Inc., 1975).

[50]*Assessment of the Capability of Firing Clean Low BTU Gases in Existing Coal, Oil and Gas-Fired Steam Generators*, PB 248328 (Combustion Engineering Corp., 1975).

Table 13
Comparative Combustion Calculations—Coal Vs. Wood Pellets
(From *Steam* [Babcock and Wilcox, Inc., 1975].)

Ultimate Analysis (% by weight)

	Example Coal	Wood Pellets
Carbon	72.8	44.4
Hydrogen	4.8	5.5
Oxygen	6.2	38.0
Nitrogen	1.5	1.0
Sulphur	2.2	—
Moisture	3.5	10.0
Ash	9.0	2.0

Required for Combustion: lb/lb fuel

	Stoichiometric		25% Excess Air	
	Oxygen	Dry Air	Oxygen	Dry Air
Example Coal	2.277	9.868	3.415	14.802
Wood Pellets	1.238	5.367	1.858	8.051

Combustion Products at 25% Excess Air: lb/lb fuel

	Carbon Dioxide	Water	Sulphur Dioxide	Oxygen	Nitrogen	Wet Weight	Dry Weight
Example Coal	2.664	0.624	0.044	0.569	9.494	13.395	12.771
Wood Pellets	1.625	0.679	—	0.310	5.157	7.771	7.092

it appears that there could be a reduction in the mass flow rate of combustion products when firing wood pellets, and that mass flow rate problems sometimes encountered with using low grade alternate fuels will be avoided with wood pellets.

On the other hand, proper combustion of wood pellets may require more than 25 percent excess air, with a proportional increase in the flow rate of combustion products. Pellets are higher in volatile matter than most coals, and the oxidation of volatiles requires good mixing, which is achieved by proper configuration of the combustion chamber and correct location and velocity of overfire air injection. The actual amount of excess air required for wood pellet combustion is therefore a function of an existing design and operating flexibility. It has been common practice in DOD wood pellet tests to increase overfire air substantially to obtain proper wood pellet combustion: during these tests the location, distribution, and controllability of overfire air have been pinpointed as important considerations affecting wood pellet use. Test data have indicated that excess air actually used has been on the order of 30 to 50 percent. Although this level will probably decrease as more operating experience is gained with wood pellets, it does not

appear that the mass flow rate of combustion products will be a strongly limiting factor in wood pellet use as a substitute fuel.

Flame Temperature

Furnace heat transfer in watertube systems is primarily radiative, and the rate of radiative heat transfer (q) is governed by the relationship

$$q = Aes\,(T^4_1 - T^4_2) \qquad [Eq\ 7]$$

where q = rate of radiative heat transfer

e = emissivity of radiating element

s = Stefan-Boltzmann constant

A = visible flame boundary

T_1 = absolute temperature of source

T_2 = absolute temperature of sink

The rate of radiative transfer depends greatly on the temperature of the flame. Theoretical flame temperatures can be calculated for virtually any fuel: for wood pellets they are above 3000°F (1649°C). In practice, actual flame temperatures are usually lower than theoretical ones for several reasons, including

heat losses, quenching, and the viscosity-temperature relationship of ash.

In DOD wood pellet tests, flame temperatures ranged between 2200°F and 2450°F (1204°C and 1343°C) for wood pellets and between 2300°F and 2600°F (1260°C and 1427°C) for bituminous coal. As indicated by Equation 7, even a small change in flame temperature can strongly affect the radiative heat transfer rate, since the absolute temperature of the flame is raised to the fourth power. Because of this, a decrease in flame temperature can be expected to effect a more than proportional decrease in radiative heat transfer rate, all other variables assumed to be constant. Therefore, the role of radiative transfer can be expected to diminish somewhat when firing wood pellets as a coal substitute.

The degree to which a decrease of any magnitude in the radiative heat transfer rate will affect overall system heat transfer is a function of existing design. Reduction in radiative transfer might be fully compensated for by an increase in the rate of heat transfer in the convective section. Such a relative shift of duty was observed during Woodex tests at Fort Benjamin Harrison, but the increase in the convective heat transfer rate did not appear to compensate fully for lost radiative transfer. Continually high flue gas temperatures during the Fort Benjamin Harrison test suggested that an enlarged convective heat transfer surface area would lead to more efficient fuel use and minimize any possible boiler derating due to changed heat transfer patterns. Another modification at Fort Benjamin Harrison would involve retubing the furnace with tubes sized and spaced appropriately to achieve the design basis radiative rate and convective inlet temperatures. Such a modification would be tantamount to increasing the radiative heat absorbing surface area; fortunately, the wood's lower ash content and its tendency to foul noticeably less would permit furnace tubes to be more closely spaced than appropriate with many coals.

Surface Effects

For a central heating or power boiler to function satisfactorily, internal surfaces must be kept clean and intact. Slagging, fouling, and corrosion are deleterious and result in poor system performance and decreased fuel economy.

DOD tests with wood pellets have been too brief to identify any but the most immediately observable surface effects attributable to pellet firing. In general, experience has been highly positive, with personnel at Kingsley AFB and Fort McCoy reporting overall decreased wear on surfaces and auxiliaries, such as fans, and corresponding levels of maintenance well below those normal with coal. Moreover, since wood pellets are lower in chlorides and sulphur, it is expected that less corrosion damage will occur.

Unfortunately, with respect to the thermochemical and thermophysical properties of wood pellet ash, there seems to be no data by which to project the effects pellet firing will have on surfaces over the moderate and long term.

Auxiliaries

To date, the effects that wood pellets have had on heating and power system auxiliaries have been entirely positive, and this has been attributed to the low ash content of the fuel. In fact, sootblowers and fans have benefited most from the use of wood pellets.

The number and location of sootblowers are determined by the fuel's ash content and the ash's fusion temperature. In DOD experience with wood pellets so far, there has been a dramatic decrease in the frequency of sootblowing, principally because of the fuel's low ash content and the tendency of that ash to remain in its carrier gas and avoid deposition.

Forced draft (FD) fan size is determined partly by fuel and air moisture content and downstream tempering air requirements. With higher moisture content, less tempering air is admitted downstream and more air must be directly forced into the furnace through the FD fan. While the moisture content of wood pellets is higher than that of coal, all FD fans at DOD wood pellet test sites have clearly demonstrated their capability to perform adequately when pellets have been used.

Ash loading and composition directly influence induced draft (ID) fan selection and performance. In general, the low ash content of the wood pellets has meant reduced ID fan power consumption and attendant decreases in boiler plant electrical power consumption. No significant problems have been encountered in any wood pellet test with respect to ID fan capability to provide adequate draft even at comparatively high levels of turndown.

Response and Turndown

The response of a larger central boiler to sudden changes in load when firing wood pellets appears adequate. During the Fort Benjamin Harrison Woodex tests, the boiler was manually subjected to rapid turnup and turndown, and its responsiveness appeared little different than when firing coal. A limiting factor during this test was feed rate; at high turnup ratios, several minutes were required under manual operation to optimize feed rate and underfire and overfire air. However, at up to 90 percent MCR, unit performance was observably satisfactory once a steady-state condition was achieved.

Turndown also appeared satisfactory for the boiler tested at Fort Benjamin Harrison. During part of the test, the unit was turned down to approximately 8500 lb/hr (3856 kg/hr) steam generation, or about 27 percent MCR. There appeared to be no problem in manually restoring a steam generation rate of about 21,000 lb/hr (9525 kg/hr) rather rapidly after operating for a few hours at less than 10,000 lb/hr (4536 kg/hr). However, during turndown there was occasionally a lot of smoke and plant personnel had to continually monitor operation.

In normal operation, the lowest a given boiler at Fort Benjamin Harrison operates is at approximately 12,000 lb/hr (5443 kg/hr), or about 39 percent MCR. At this level of operation, firing wood pellets represented no observable operating difficulty other than the need for the boiler to be operated in manual mode.

Based on the Fort Benjamin Harrison wood pellet test, it appears that acceptable boiler responsiveness can be anticipated when firing wood pellets and that normal turndown levels of operation can be achieved with little difficulty. However, at and below about 30 percent MCR there may be some problems in achieving desired high levels of efficiency in fuel use. Similar problems also are typically encountered when firing coal at about 25 percent MCR in the spreader stokers at Fort Benjamin Harrison.

Controls

Throughout DOD wood pellet tests, use of existing boiler controls (nearly all pneumatic) when firing wood pellets has been somewhat difficult, and often the boilers have been operating manually. Part of the difficulty in using automatic controls has been the operating personnel's unfamiliarity with wood pellets

and inability to readily set optimal automatic control points for the use of pellets. Normally, several days of experimentation are required before operators can establish reliable automatic operation. At Kingsley AFB, where wood pellets have been used for about 18 months, and at Fort McCoy, where they have been used for about 6 months, automatic boiler operation has been successful after a brief indoctrination period in manual mode.

Control difficulties appear to center on the correct apportioning of underfire and overfire air, and it appears that finer controls of these variables are needed for wood pellets than are usually provided for coal. In many DOD wood pellet tests, the fuel was burned at higher excess air rates than normally would be optimal; this happened largely because combustion air flow rates could not be finely modulated with existing coal-designed equipment. In some cases, such equipment may be marginally adequate for acceptable wood pellet combustion, but plant operators almost unanimously agree that finer controls would make operation easier, thus increasing fuel economy and thereby the cost-effectiveness of wood pellet use.

Firing Mixtures of Wood Pellets and Coal

Firing mixtures of wood pellets and coal during DOD tests was only partially successful because this procedure caused problems with fuel-mixing techniques, incomplete combustion, and increased levels of particulate density in flue gases.

Generally, central heating and power plants do not have in-place equipment to blend two fuels before the mixture is fired. At Fort Benjamin Harrison, mixing was accomplished by alternating the fuels fed to the weigh larry and distributed to the frontwall feed hopper of the boiler. At Fort McCoy, mixing was accomplished by alternating bucketfuls of fuel manually charged to the small heating plant feed hoppers. In both cases, relatively good mixtures were achieved, and the substitution ratio of wood pellets was controllable. For long-term practice, either procedure appears acceptable but is relatively labor intensive. In some cases, coal and wood pellets could be mixed outside the boiler plant and the mixture delivered to a bunker in the same way coal usually is. This method, however, will add a major overpressure effect to the wood pellets and could cause structural deterioration—a condition which could make their handling and firing difficult, depending on the design of the existing system.

During the Fort Benjamin Harrison and Fort McCoy wood pellet tests, the simultaneous combustion of pellets and coal produced clinkering problems which were not observed when either fuel was fired alone. It was hypothesized that the wood pellets, which volatilize and ignite at significantly lower temperatures than coal, tended to quench coal combustion. Clinkering appeared to be most severe in the underfeed retort stokers at the small Fort McCoy heating plants, particularly when volumetric pellet-coal blends were 1:1 and higher, representing a wood pellet substitution rate of about 35 percent by as-fired heating value. Noting the combustion performance data in Table 12, the tendency of fuel to cake is particularly important in traveling grate stokers, relatively less important in spreader stokers, and moderately important in underfeed stokers. While clinkering appeared to be less a problem at Fort Benjamin Harrison (spreader stoker) than at Fort McCoy, it nevertheless did occur when fuel mixtures were fired, and was accompanied by locally transient blowholes and comparatively high levels of smoke.

The relative incompatibility of pellets and coal during combustion presents some difficulty in firing a mixture of the two fuels. As was earlier demonstrated, use of substitute wood pellets requires that grate travel speed be increased substantially. This is due both to greater fuel feed rate required to maintain furnace heat and to the relatively rapid combustion rate of wood pellets compared to most coals. At higher pellet substitution rates particularly, grate travel speed could be faster than required for proper coal combustion and burnout, especially since the rate of coal combustion may be somewhat reduced by the quenching effect of more "coolly" burning wood pellets. Such a condition easily could result in incomplete coal combustion (measured as combustibles remaining in bottom ash) and decreased effectiveness of coal use.

Whether such co-combustion problems will occur is a function of the existing boiler design being considered for alternate fuel use. Based on the wood pellet tests conducted, however, it appears that substitute, rather than supplemental, wood pellet firing will offer the best results.

Summary

Wood pellets are a highly oxygenated fuel with a significantly greater volatile matter content and about two-thirds the heating value of most bituminous coals.

These differences — coupled with size consistency (fines), caking tendency (pellet-coal mixtures), and low ash content — are important factors limiting the use of wood pellets as substitute for and supplement to coal in existing Army-scale coal-designed boilers.

Use of wood pellets as a coal substitute appears to be limited by the capability of coal-designed equipment to accommodate the high feed rates required to maintain furnace heat. Depending on the design of the feeder and boiler system, feeding considerations alone can mean derating of up to 48 percent when using pellets, with 10 to 20 percent probably typical over long-term use. Because of the low ash content of the fuel and its low fraction of sulphur and nitrogen as compared to coal, wood pellet use will probably reduce surface corrosion of boiler internals and place less demand on the boiler draft system, with attendant savings in maintenance and electrical power. Because wood has flame temperatures somewhat lower than coal, using pellets may cause a shift of relative duty between radiant and convective heat transfer sections, and, depending on the system, may mean some loss of fuel-to-product efficiency.

It is questionable whether automatic controls for boilers designed to fire coal can provide optimal wood pellet combustion. Both underfire and overfire air must be carefully modulated, and controls in some plants cannot be adjusted precisely enough to optimize combustion air. In manual modes of operation, optimization has been approached more closely, particularly in controlling boiler turndown and turnup in response to sudden changes in demand. Based on short-term tests, boiler responsiveness appears to be relatively good when firing wood pellets, but the achievable turndown is about 30 percent of MCR, and hence not quite as good as with coal. Nevertheless, for typical boiler operation, where turndown rarely is lower than about 39 percent, there should be no serious problems with pellets.

DOD wood pellet tests demonstrated that when firing pellets mixed with coal at 35 percent by heating value and higher, there was a tendency for coal to clinker, sometimes severely. This was attributed to the "cooler" combustion temperatures and generally more rapid combustion rate of pellets compared to those characteristics of the coal tested. The result was a tendency of pellets to inhibit optimal coal combustion. This characteristic was observed to be less severe in spreader stokers than in underfired stokers, and it is expected that it will be a problem in traveling

grate stokers. Because of this, wood pellets were viewed more usable as a coal substitute than as a coal supplement.

6 ENVIRONMENTAL CONSIDERATIONS

General

Any installation that plans to become involved in forest management, harvestation, and wood pellet production must consider the associated environmental consequences. Except for pellet production, these impacts are almost exclusively site specific and therefore difficult to generalize; nonetheless, some literature on this subject is available and should be consulted.[51] Costs for an environmental impact assessment can vary between $10,000 and $40,000, while those of a complete statement are higher and can be as great as $250,000.

This chapter is concerned only with the major environmental considerations involved in the *use* of wood pellets, however, since relatively few installations are expected to consider manufacturing them from local biomass resources in the near future. The number of commercial wood pellet vendors is increasing, and many installations will soon be able to procure and use the alternate fuel. Of chief interest are not only the environmental impacts of wood pellet use, but also how these impacts compare to those associated with coal use.

Analyses of wood pellet use and several tests of wood pellets in coal systems indicate that use of wood pellets — as opposed to coal — is almost entirely beneficial because the pellets have less impact on water, land, and air.

Water

Any installation burning coal with an appreciable sulphur content faces the prospect of flue gas desulphurization to keep emissions of gaseous sulphur dioxide within prevailing limits. Wet scrubbers are the best available technology for this, even though their reliability is still highly questionable.[52] Wastewater quantities ranging up to 500,000 kgal/year (1 875 000 m^3/yr) will require treatment for removal of contaminants.[53] A detailed study at a large Army ammunition plant indicated that limestone/lime scrubbing of flue gases when firing coal at a major boiler house would result in 350,000 gal/day (1268 m^3/day) slurry containing 10 percent by weight solids.[54] Wood pellet firing will require no such air pollution control system because of the negligible sulphur content of the fuel, and hence will avoid potential environmental problems and costs associated with flue gas desulphurization.

Wet ash treatment systems (either direct quench or steam ejection of dry ash) will result in some wastewater contamination. Table 14 presents the composition of coal and wood ash. Values for coal are stated as ranges, while those given for wood are single averages. Note that wood ash contains a wider variety of elements and compounds than coal ash, which contains higher concentrations of SiO_2, Al_2O_3, Fe_2O_3, TiO_2, and SO_3. Wood ash, on the other hand, has higher concentrations of CaO, MgO, MnO, P_2O_5, and M_2O, with calcium oxide clearly dominating. Thus, from the standpoint of wastewater used in ash systems, wood pellets may require a somewhat greater treatment than coal.

Land

Disposal of ash is a major land impact to be dealt with when either coal or wood pellets are used. From the data presented in Table 14, it appears that the physical constraints placed on land disposal of coal ash might equally apply to that of wood pellet ash, although quantitatively less ash is generated from pellet combustion. Because of its mineral content, wood ash has been widely considered as a fertilizing agent both alone and when blended with other chemicals. Its applicability at a given location depends on soil conditions and type of vegetation, but it generally has widespread promise.

[51]Stephen H. Spurr, "Silviculture," *Scientific American*, Vol 240, No. 2 (1979), pp. 76-91; A. B. Curtis, Jr., "Wood for Energy: An Overview," *Forest Products Utilization Bulletin* (U.S. Forest Service, September 1978); A. Meyer, *Return to Wood as a Major Fuel Source* (Chase Manhattan Bank, 1978); *Preliminary Environmental Assessment of Biomass Conversion to Synthetic Fuels*, PB289775 (Battelle-Columbus Laboratories, 1978).

[52]W. Megonnell, "Efficiency and Reliability of Sulfur Dioxide Scrubbers," *Journal of the Air Pollution Control Association*, Vol 28, No. 7 (July 1978), p. 7.

[53]S. A. Hathaway, M. Tseng, and J. S. Lin, *Project Development Guidelines for Converting Army Installations to Coal Use*, Interim Report E-148/ADA068025 (CERL, March 1979).

[54]B. A. Donahue, S. A. Hathaway, G. Schanche, and S. R. Struss, *Evaluation of Alternatives for Restoring the South Boiler House at Joliet AAP to High-Sulfur-Coal Burning Capability*, Technical Report N-66/ADA069374 (CERL, May 1979).

Table 14

Composition of Coal and Wood Ash

Fuel	SiO	Al O	Fe₂O	CaO	CaCO	MgO	MnO	P O	K O	M O	TiO	S O	Mn O	Na O	Cl
Jack Pine	16.0	6.3	5.0	51.6	4.9	5.5	1.6	2.0	4.1	3.1	0.2	2.6	-		
Birch	3.0		2.9	58.2	13.0	4.2	4.6	2.9	6.6	1.3	T	3.2	-		
Maple	9.9	3.8	1.7	55.5	1.4	19.4	1.0	1.1	5.8	2.2	T	1.4	-	-	-
E. Hemlock	10.0	2.1	1.3	53.6	9.7	13.1	1.2	2.1	4.6	1.1	T	1.4	-		
Pine Bark	39.0	14.0	3.0	25.5	-	6.5	-	-	6.0	-	0.2	0.3	T	1.3	T
Oak Bark	11.1	0.1	3.3	64.5	-	1.2	-	-	0.2	-	0.1	2.0	T	8.9	T
Spruce Bark	32.0	11.0	6.4	25.3	-	4.1	-	-	2.4	-	0.8	2.1	1.5	8.0	T
Anthracite	48-68	25-44	2-10	0.2-4	-	0.2-1	-	-	-	-	1.0-2	0.1-1	-	-	T
Bituminous	7-68	4-39	2-44	0.7-36	-	0.1-4	-	-	0.2-4	-	0.5-4	0.1-32	-	0.2-3	
Subbituminous	17-58	4-35	3-19	2.2-52	-	0.5-8	-	-	-	-	0.6-2	3.0-16	-	-	-
Lignite	6-40	4-26	1-34	12.4-52	-	2.8-14	-	-	0.1-1.3	-	7-0.8	8.3-32	-	0.2-28	-

T = trace amount

Sources: *Combustion Engineering* (Combustion Engineering Corp., 1966); *Steam* (Babcock and Wilcox Co., 1975); *Mineral Matter and Trace Elements in U.S. Coals* [Pennsylvania State University, 1972].

In the case of coal firing, use of flue gas desulphurization systems will result in wastewater containing a variety of contaminants. Disposal of dewatered sludge will present a land-use problem, particularly in light of the relatively vast quantities generated. Moreover, sludge dewatering itself would significantly impact the land environment. In one Army coal conversion study, it was determined that a chemical stabilization pond with an area of 100 acres (40.5 ha) would be required for a slurry containing 10 percent by weight solids. In comparison, mechanical dewatering would require chemical stabilization and would produce 260 tons/day (234 MT/day) of a filter cake containing 60 percent solids. The filter cake would be landfilled, and the supernatant would be recycled to the desulphurization system or chemically treated and discharged.[55] This waste generation rate of 260 tons/day (234 MT/day) is more than seven times greater than the average peacetime Army installation solid waste generation rate.[56] The land impact of flue gas desulphurization sludge disposal is highly significant when compared to the scale of average installation landfill disposal facilities, and it will be avoided if wood can be used as a substitute for coal.

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[55] B. A. Donahue, S. A. Hathaway, G. Schanche, and S. R. Struss, *Evaluation of Alternatives for Restoring the South Boiler House at Joliet AAP to High-Sulfur-Coal Burning Capability,* Technical Report N-66/ADA069374 (CERL, May 1979).

[56] S. A. Hathaway, *Recovery of Energy from Solid Waste at Army Installations,* Technical Manuscript E-118/ADA044814 (CERL, August 1977).

Quantitatively, use of wood pellets should result in much-reduced consumption of landfill. Pellets contain about 10 percent by weight of the ash found in most coals, meaning at least a 90 percent reduction of land use for disposal in a typical installation-scale application. Moreover, if all ash could be recycled as a fertilizer or otherwise used, landfill disposal at heating and power plant residues could be eliminated.

Air

As indicated above, use of wood pellets will allow an installation to avoid the necessity of employing currently high-risk and costly flue gas desulphurization systems. Moreover, as evidenced by results of DOD wood pellet tests, particulate emission rates normally associated with coal are reduced by at least half when wood pellets are used on a substitute basis. At many locations, use of pellets will reduce particulate emissions enough so that hardware need not be added to achieve compliance. At other locations, where particulate emissions from wood pellets are lower than from coal but still noncompliant, further reduction to compliant levels can be achieved without using costly high-efficiency removal hardware required when firing coal. Emission of nitrogen oxides when firing wood pellets should not be significant, since flame temperatures are nowhere near the levels required to generate substantial quantities of the material.

Another significant benefit of using wood as a coal substitute is that wood does not introduce low level

Table 15
Economic Data

Item	Unit Cost	Short-Term Escalation Rates (%/Yr)			Differential Escalation Rate (%)	20-Year Present Worth Factor
		FY80	FY81	FY82		
Design and Construction	—	6.5	6.0	6.0	—	—
Electrical Power	$0.03/kWh	15.0	14.0	14.0	7.0	15.101
Wood Pellets	$2.60/MBtu ($2.46/kJ)	15.0	14.0	14.0	7.0	15.101
Coal	$1.75/MBtu ($1.66/kJ)	10.0	10.0	10.0	5.0	12.774
Labor	$25,000/M-Y	6.5	6.0	6.0	0.0	8.939
Water	$0.50/kgal ($0.13/m³)	6.0	5.5	5.0	0.0	8.939
Maintenance and Repair	—	6.5	6.0	6.0		8.939
Ash Disposal	$6.00/ton ($6.61/MT)	6.5	6.0	6.0	0.0	8.939
Sludge Disposal	$10.00/ton ($11.02/MT)	6.5	6.0	6.0	0.0	8.939
Chemicals (FGD System)	—	6.5	6.0	6.0	0.0	8.939
Dry Scrubber Media	$15.000/yr	6.5	6.0	6.0	0.0	8.939

radioactive materials into the atmosphere. In contrast, the annual radioactive effect of a 1000 MW coal-fired power plant firing a representative 1980 mixture of coal has been projected to be 0.002 Curies of radium (226) and 0.006 Curies of radium (228).[57]

Any low-level radioactive emission from firing wood will represent only transfer of such materials already within the ecosphere with the result that there will be no net radioactive gain in the air, water, and land surface environments.

Summary

From a general environmental standpoint, wood pellets can be considered far cleaner than coal. An Army installation using wood pellets will realize its greatest financial and environmental benefits in being able to avoid both retrofit of flue gas desulphurization systems and corresponding environmental impacts associated with dewatering and disposal of vast quantities of sludge. In general, the environmental

Consideration of Health Benefit-Cost Analysis for Activities Involving Ionizing Radiation Exposure and Alternatives. EPA 520/4-77-003, PB286555 (U.S. Environmental Protection Agency, 1977).

impacts of using wood pellets as a substitute for coal can be considered highly favorable when compared to the impacts associated with coal use.

7 ECONOMICS OF DENSIFIED BIOMASS USE

General

This chapter deals with whether wood pellets can be a cost-effective, environmentally compatible substitute for coal—a substitute which can produce energy meeting peacetime needs at an average Army central power plant. Two scenarios are considered, namely: the cost and benefits of using wood pellets as a substitute for (1) low-sulphur and (2) high-sulphur coal. The analysis is admittedly general, since many costs and benefits associated with fuel substitution are highly site specific and must be evaluated on a case-by-case basis. The scenarios are intended to represent general "worst cases" in order to show how affordable wood pellet use is, and to discuss a concept for implementing the alternate fuel on Army fixed facilities and installations.

Economic Data and Assumptions

Table 15 provides economic data used in evaluating each of the two fuel-substitution scenarios. Unit costs shown are average costs for each line item at the end of FY79. Short-term and long-term differential escalation rates are the same as applied elsewhere in similar fuel-substitution analyses.[58] The 20-year, present-worth factor was computed using the following equation:

[Eq 8]

$$PWF = \sum_{n=0}^{20} \left\{ \left[\frac{1}{(1 + I - i)^n} + \frac{1}{(1 + I - i)^{n-1}} \right] / 2 \right\}$$

where PWF = 20-year present worth factor

I = discount rate ($= 0.10$)

i = long-term fractional differential escalation rate

n = integer year of economic life.

Several assumptions underlie the data in Table 15. First, the cost of wood pellets is somewhat low but within the range of prices paid for such material to support DOD tests. This cost reflects an assumed local supply, so that transportation distances are minimal. To reflect a "worst case" analysis, the escalation rates assigned to wood pellets are the same as those given to electrical power. This assumption was also based on the fact that power is a major cost associated with pellet production. Second, labor costs are assumed to be $25,000/man-year, including benefits, and are to be taken as the total cost of an employee to his/her employer. While a supervisor will cost more than a laborer in an average work crew, a single cost was assumed here to represent a rough average cost. Third, ash disposal costs are for bottom ash and fly ash in a dry state taken to an installation landfill for disposal. Costs of sludge disposal are higher and reflect the average cost of dewatering and solids disposal. Finally, chemicals are given as an annual cost and were estimated for a limestone scrubbing system requiring 6000 tons/yr (10,800 MT/yr) of materials for a boiler rated 40 MBtu/hr (12 MWt). Estimated material cost was on the order of $20,000/ton ($21.98/MT).[59]

[58]S. A. Hathaway, A. N. Collishaw, and J. S. Lin, *Recovery of Waste Energy at Naval Submarine Base, New London, Connecticut,* Technical Report E-138 (Naval Facilities Engineering Command [NAVFAC]. November 1978); *Revised Energy Conservation Investment Program Guidance* (DA, April 1977).

[59]S. A. Hathaway, M. Tseng, and J. S. Lin, *Project Development Guidelines for Converting Army Installations to Coal Use,* Interim Report E-148/ADA068025 (CERL, March 1979).

Assumptions commonly underlying the following analyses include a system startup of the first day of FY83 and a 20-year system life. Operation of all systems was assumed to be an 0.65 annual mean peacetime load with an availability of 0.85, including scheduled and unforeseen outage. It was also assumed that within the 20-year life there would be no major cyclic repair or replacement of equipment. Finally, in the case of using wood pellets as a substitute primary fuel in each of the two scenarios, application of the dry granular media scrubber (DGMS) was assumed to be sufficient to reduce particulate emissions to within compliant levels. Currently, 12 DGMS systems are in operation throughout the country, and a recent study of SCS Engineers for the Army pointed to its applicability for reducing particulate emissions from installation-scale wood-fired boilers.[60] While the DGMS might not have enough particulate removal efficiency to be effective when used on extremely noncompliant systems, it appears to achieve compliance successfully when unabated particulate emissions are close to compliant levels, as is the case with wood pellet firing.

Substituting Wood Pellets for Sulphur-Compliant Coal

In this scenario, a 40 MBtu/hr (12 MWt) power boiler is firing low-sulphur coal. The plant complies with emission guidelines for sulphur and nitrogen oxides but none with particulate emission guidelines. To reduce emission of particulate matter, the installation considers the following two alternatives: (1) retrofit Teflon-media baghouse to the plant, or (2) fire substitute wood pellets and retrofit a DGMS for particulate pollution abatement. It is assumed that whichever alternative is selected, startup will be on the first day of FY83.

For the first alternative (baghouse) the total turnkey first cost is $2,900,000 in FY83 dollars. The present-worth, annual-cost analysis in Table 16 indicates that the first cost is about 32 percent of the total, present-worth, annual cost of $9,138,400 (FY83 dollars). Excluding fuel, the analysis shows that the major annual costs are power, labor, and bag replacement. Baghouse costs shown in Table 16 were estimated

[60]B. West and J. Woodyard, *Assessment of Dry Granular Media Scrubbers for Abatement of Particulate Emissions From Stationary Point Combustion Sources on Army Fixed Facilities and Installations* (SCS Engineers, Long Beach, CA, 1979).

Table 16

Cost Comparison for Scenario 1

	Alternative 1: Baghouse			Alternative 2: Pellets and DGMS	
Item	Quantity/Yr	Present Worth Cost (k$)	Item	Quantity/Yr	Present Worth Cost ($)
Electrical	968,000 kwh	655.4	Electrical	246,560	166.9
Labor	1½ Man Yr	403.4	Labor	½ Man Yr	133.7
Maintenance and Repair	Bags @ $32k/yr Misc. @ $8k/yr	342.3 85.6	Maintenance and Repair	Media @ $15k/yr Misc. @ $10k/yr	160.5 107.0
Ash Disposal	1,128 tons/yr (1023 mt/yr)	72.4	Ash Disposal	119 tons/yr (108 mt/yr)	7.6
Coal	254,732 MBtu/yr (268 742 GJ/yr)	7,579.3	Wood Pellets	276,566 MBtu/yr (291 777 GJ/yr)	16,228.8
Subtotal (k$)		9,138.4			16,804.5
Capital Cost (k$)		2,900.0			1,350.0
Total Present Worth Cost (k$)		12,038.4			18,184.5
Fuel Adjustment		N.A.*			-7,579.3
Adjusted Total Present Worth Cost		12,038.4			10,605.2

*Not applicable.

from existing literature.[61] The total, present-value cost of the baghouse alternative is about $12,000,000.

Table 16 also shows costs for the second alternative, fuel substitution, and use of a DGMS for particulate control. A turnkey capital cost of $1,350,000 (FY83 dollars) is required, including retrofit DGMS and a bin and feeding system for 250 tons (225 MT) of wood pellets. Besides fuel, significant recurring cost items are power, labor, and filtration media, but all are less than for baghouse operation. Significantly, pellet costs are very high. Because of less efficiency (0.70 compared to 0.76 for coal), more energy in pellets must be purchased. Without a fuel adjustment, the total, present-worth cost in FY83 dollars is $18,184,500. Adjusting for fuel expenditures of $7,579,300 which

[61] S. A. Hathaway, M. Tseng, and J. S. Lin, *Project Development Guidelines for Converting Army Installations to Coal Use*, Interim Report E-148/ADA068025 (CERL, March 1979); G. Schanche, S. A. Hathaway, and J. Oxley, *Technical and Economic Guide for Air Pollution Control Systems*, Draft Technical Report (CERL).

would have been made for boiler operation regardless of the pollution control strategy, this alternative has FY83 present-worth total cost of $10,605,200, or $1,433,200 less than the baghouse alternative.

Fuel is a significant cost under the wood pellet alternative. The indicated present-worth wood pellet cost of approximately $17,000,000 (FY83) is probably an overestimate, since short- and long-term escalation rates used to compute the cost based to FY83 were relatively high rates of increases normally applied to electrical power. If on the other hand, coal escalation rates were applied, the wood pellets' FY83 present-worth cost would have been $12,225,800 (27 percent less), and the total, fuel-adjusted, present-worth cost of the wood pellet alternative would have been $6,572,000, or just over half of the cost of the baghouse alternative. In addition, cost savings associated with reduced maintenance and repair (due to improved wood ash properties) have not been quantified, but could make the wood pellet alternative even more economically attractive compared to the baghouse alternative.

Table 17
Cost Comparison for Scenario 2

	Alternative 1: FGD			Alternative 2: Pellets and DGMS	
Item	Quantity/Yr	Present Worth Cost (k$)	Item	Quantity/Yr	Present Worth Cost (k$)
Electrical	3,770,000	2,552.6	Electrical	246,560	166.9
Labor	4½ Man-Years	1,203.4	Labor	½ Man-Year	133.7
Maintenance and Repair	4% of Capital Cost of $3,500k	1,497.5	Maintenance and Repair	Media @ $15k/yr Misc. @ $10k/yr	160.5 107.0
Sludge Disposal	8,000 tons (7256 MT)	855.7	Ash Disposal	119 tons/yr (108 MT/yr)	7.6
Water	20,000 kgal/yr (75 700 m³/yr)	107.0	Wood Pellets	276,566 MBtu/yr (291 777 GJ/yr)	16,228.8
Limestone	6,000 tons (5442 MT)	1,283.6			
Chemicals	10 Tons (9.1 MT)	3.7			
Coal	280,205 MBtu (295 617 GJ)	8,337.2			
Subtotal (k$)		15,840.7			16,804.5
Capital Cost (k$)		3,500.0			1,350.0
Total Present Worth Cost (k$)		19,340.7			18,184.5
Fuel Adjustment		—			-7,579.3
Adjusted Total Present Worth Cost ($k)		19,340.7			10,605.2

Substituting Wood Pellets for Sulphur-Noncompliant Coal

In this scenario, a 40 MBtu/hr (40 MWt) power boiler is firing coal having a sulphur content on the order of 4 percent by weight. The plant complies with emission guidelines for nitrogen oxides but not with locally prevailing guidelines for sulphur oxides and particulate matter. The installation considers two alternatives to bring air pollutant emissions within compliance: (1) retrofitting a flue gas desulphurization (FGD) system which will simultaneously reduce particulate emissions; and (2) firing substitute wood pellets and retrofitting a DGMS for particulate pollution abatement. Startup of the chosen system will be on the first day of FY83.

For the FGD system, the total turnkey first cost is $3,500,000 in FY83 dollars. The present-worth, annual

cost analysis in Table 17 indicates that the first cost is about 22 percent of the present-worth annual cost of $15,840,700. Excluding fuel, the analysis shows that the major annual costs are power and maintenance and repair, with those of limestone (scrubber sorbent) and labor being significant. Scrubber costs were estimated according to the same procedure by which baghouse costs were obtained in the above discussion. The total present-worth cost of the FGD alternative is approximately $19,300,000.

Table 17 also shows cost data for the wood pellet-DGMS alternative, which are the same as tabulated earlier for the first scenario. In computing the present-worth costs for this alternative, a fuel cost adjustment of $7,579,300 was made. However, under the FGD alternative, a present-worth expenditure of $8,337,200

for coal is listed. This expenditure reflects an additional 10 percent fuel requirement to produce steam used for stack gas reheat after the scrubber; the additional amount is not creditable under the wood pellet-DGMS alternative. The wood pellet alternative has a total present-worth cost of $10,605,200, or only 45 percent of the cost of the FGD alternative. The effective savings of $8,735,500 is more than enough to pay for the capital investment, all electrical power, labor, maintenance and repair, and ash disposal costs, plus a substantial portion of the wood pellets for this alternative.

Cost of Wood Pellets

Whether an installation can afford to use wood pellets depends not only on the as-delivered cost of the fuel and the alternative systems to which that fuel's economic attributes can be compared, but also on the conditions of use.

The general analyses above indicate that for the average installation central boiler, using substitute wood pellets can be cost-effective compared to the stated alternatives and given the assumptions mentioned at the beginning of this chapter. The break-even cost of pellets for each scenario can be computed using the following equation:

$$W = \frac{P_p + (PC_2 + [PC_1 - PC_2])}{E \times M} \qquad [Eq\ 9]$$

where   W = cost of wood pellets to break even

P_p = present worth cost of pellets

PC_2 = total present-worth cost of Alternative 2

PC_1 = total present-worth cost of Alternative 1

E = cumulative escalation rate (= 22.569)

M = MBtu/yr pellets required

Applying this to the first scenario:

$$W = \frac{\$16,228,800 + (\$10,605,200 + [\$12,038,400 - \$10,605,200])}{(22.569)(276.566)} =$$

$$\$4.53/MBtu\ (\$4.30/kJ). \qquad [Eq\ 10]$$

Applying Equation 9 to the second scenario, it is found that the cost of pellets in order for the total

present value cost of the two alternatives to be equal is $5.70 MBtu ($5.41/kJ). Both figures are within the range of wood pellet costs paid to support DOD wood pellet testing, as reported earlier in this report.

Use of substitute wood pellets will probably result in both efficiency loss and derating of a central boiler, as mentioned before. If the plant selected for conversion can be operated under these conditions, in some cases the benefits (future avoided costs) of using pellets are achievable. If it cannot, then a detailed study of the technical/economic feasibility of wood pellet use at the specific site should be conducted, particularly to examine the possibility of changing relative boiler duty in a central plant to permit wood pellet use. In either case, the affordable price to be paid for wood pellets must be determined by considering the cost of other alternative fuels that might provide efficient, energy-effective, and environmentally compatible operation of the central heating or power plant.

8   CONCLUSIONS

DOD experience with the use of densified biomass (principally wood pellets) has ranged from well-instrumented, short-term experiments to continued use as a coal substitute for approximately 18 months. This experience has both led to justifiable optimism and shown the technical and economic limitations of using the alternate fuel in small heating plants and installation-scale central power plants.

A wood pellet production plant of sufficient capacity to fuel an average central power boiler is technically feasible and requires a capital investment ranging between $1,100,000 and $1,300,000. Wood pellets currently can be produced for between about $1.06/MBtu ($1.01 kJ) and $1.78/MBtu ($1.70 kJ). Production cost is highly influenced both by electrical power consumption and raw material (hogged or chipped wood) cost. An energy analysis indicates that 181 kWh/ton (716 mJ/MT) input material, or 329 kWh/ton (1298 mJ/MT) output basis, is required for pellet production. While raw material cost for the pelleting process averages about $6.00/ton ($6.67 MT) presently, there are indications that increased demand could raise prices to $12.00/ton ($13.33 MT) or more.

Technology for handling, storing, and feeding chips, hogged wood, and pellets is state of the art. A storage and feeding system for enough wood pellets to fire an average installation central power boiler at full load for 3 days is technically achievable using modern theory and practice which quantifies the unique properties of the bulk material. The capability of existing coal bunkers to reliably handle and feed wood pellets is somewhat doubtful unless modifications are made. Important quantifiable parameters influencing bunker performance of wood pellets are bulk density, solid-wall kinematic angle of friction, solid effective angle of internal friction, and the solid-wall coefficient of friction. In general, the parameters are not the same for coal and wood pellets, and a storage and feeding system for each requires a different design.

Combustion performance of wood pellets as a coal substitute has generally been satisfactory. Substitution appears to be accompanied by a loss in fuel-to-product conversion efficiency and a drop in achievable boiler load. The extent to which either or both will occur depends on the design of the boiler firing the pellets. Limiting factors include feed rate for low energy density pellets (compared to coal), the higher reactivity of pellets and their tendency to combust at lower temperatures than coal, and lower flame temperature (and hence rate of radiative heat transfer) of pellets. Efficiency losses can be as high as 15 percent, while loss of load can be up to 48 percent, depending on the boiler design. Responsiveness to sudden load changes when firing substitute pellets appears to be adequate, but turndown capability is somewhat less than for coal. Generally, finer control of overfire and underfire air than normally provided with coal-fired boilers is needed for optimal wood pellet combustion. Promising aspects of wood pellet use include very low ash content, negligible sulphur content, and potentially less wastage of internal boiler surfaces. Firing pellet-coal mixtures has generally resulted in clinkering and overall poor combustion performance. This has been attributed partly to the quenching effects by the more reactive and coolly burning pellets.

Compared to coal firing, use of wood pellets will have generally fewer adverse impacts on the air, water, and land environments; in fact, wood pellet ash has been considered for use as a fertilizing agent. With quantitatively less ash content than coal, wood pellets will dramatically reduce or totally eliminate the rate of land consumed by waste disposal. Since wood pellets have virtually no sulphur, environmental problems associated with sulphur oxide emissions and their abatement and byproduct disposal in wet removal systems will be avoided.

Use of wood pellets as a coal substitute for environmentally compatible energy production can be cost-effective for the average installation's central heating or power plant. The avoided costs of high-efficiency particulate filters and flue gas desulphurization systems significantly contribute to this economy. Wood pellets appear to be a viable substitute in stoker-fired boilers so long as some efficiency loss and some sacrifice or maximum continuous rating can be tolerated at the plant where they are considered for use.

9 RECOMMENDATIONS

Based on the findings of this investigation, Army installations currently firing coal by mechanical stokers are candidates for using substitute wood pellets if their heating and power plants can tolerate some loss in fuel-to-product conversion efficiency and some sacrifice of maximum continuous rating. It is therefore recommended that installations proceed to determine whether wood pellets are available, applicable, and affordable for use as a coal substitute in their power plants.

It is also recommended that technical specifications for wood pellet procurement Army-wide be defined and standardized to facilitate wood pellet use.

It is finally recommended that use of wood pellets at installation heating and power plants be subject to medium- and long-term monitoring, both to validate the technical-economic concepts of using substitute wood pellets and to identify technological gaps and opportunities, the investigation of which will lead to more efficient, cost-effective, and environmentally compatible systems for Army fixed facilities and installations.

REFERENCES

Army Energy Plan, ADA057987 (Headquarters, Department of the Army [DA], 1978.

Arola, R., *Wood Fuels — How Do They Stack Up?* (Energy and the Wood Products Industry, Forest Products Research Society, Madison, WI, 1976).

Assessment of the Capability of Firing Clean Low BTU Gases in Existing Coal, Oil and Gas-Fired Steam Generators, PB 248328 (Combustion Engineering Corp., 1975).

Atmospheric Emission and Performance Evaluation of Frajon Fuel Pellet (Alsid, Snowden and Associates, Bellevue, WA, 1978).

Combustion Engineering (Combustion Engineering Corp., 1966).

Considerations in Selecting Wood as an Immediate Source of Reliable and Economical Energy for Military Installations, FESA-TS-2061/ADA071791 (U.S. Army Facilities Engineering Support Agency [FESA], 1978).

Consideration of Health Benefit-Cost Analysis for Activities Involving Ionizing Radiation Exposure and Alternatives, EPA 520/4-77-003, PB 286555 (U.S. Environmental Protection Agency, 1977).

Curtis, A. B., Jr., "Wood for Energy: An Overview," *Forest Products Utilization Bulletin* (U.S. Forest Service, Div of State and Private Forestry Areas, Southeast, September 1978).

Donahue, B. A., S. A. Hathaway, G. Schanche, and S. R. Struss, *Evaluation of Alternatives for Restoring the South Boiler House at Joliet AAP to High-Sulfur-Coal Burning Capability*, Technical Report N-66/ADA069374 (CERL, May 1979).

Facilities Engineering Summary of Operations, FY77 (DA, Office of the Chief of Engineers, 1978).

General Catalogue 900 (Link Belt Corp, 1950).

Hathaway, S. A., A. N. Collishaw, and J. S. Lin, *Recovery of Waste Energy at Naval Submarine Base, New London, Connecticut*, Technical Report E-138 (Naval Facilities Engineering Command [NAVFAC], November 1978).

Hathaway, S. A. and J. S. Lin, "Combustion Rates of RDF," *Proceedings of Third International Conference on Environmental Problems in the Extractive Industries* (Wright Corp., Dayton, OH, 1977).

Hathaway, S. A. and J. Lin, *Thermogravimetric Analysis of Solid Refuse-Derived Fuels and Coal*, Technical Report E-149/ADA067829 (U.S. Army Construction Engineering Research Laboratory [CERL], March 1979).

Hathaway, S. A., M. Tseng, and J. S. Lin, *Project Development Guidelines for Converting Army Installations to Coal Use*, Interim Report E-148/ADA068025 (CERL, March 1979).

Hathaway, S. A. and R. J. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Interim Report E-110/ADA042578 (CERL, July 1977).

Hathaway, S. A., *Recovery of Energy from Solid Waste at Army Installations*, Technical Manuscript E-118/ADA044814 (CERL, August 1977).

Hiser, M., ed., *Wood Energy* (Ann Arbor Science, 1978).

Jenike, A., *Flow of Solids in Bulk Handling Systems/Flow of Bulk Solids in Bins*, Engineering Experiment Station Bulletin 64 (University of Utah, 1954).

Jenike, A., *Gravity Flow of Bulk Solids* (University of Utah, Engineering Experiment Station, 1961).

Jenike, A., *Storage and Flow of Solids*, Engineering Experiment Station Bulletin 123 (University of Utah, 1970).

Johanson, J., "Design for Flexibility in Storage and Reclaim," *Chemical Engineering*, Vol 85, No. 24 (30 October 1978).

Johanson, J., "Know Your Material — How to Predict and Use the Properties of Bulk Solids," *Chemical Engineering*, Vol 85, No. 24 (30 October 1978).

Koehler, A. *The Properties and Uses of Wood* (McGraw-Hill, 1924).

Megonnell, W., "Efficiency and Reliability of Sulfur Dioxide Scrubbers," *Journal of the Air Pollution Control Association*, Vol 28, No. 7 (July 1978).

Meyer, A., *Return to Wood as a Major Fuel Source* (Chase Manhattan Bank, 1978).

Preliminary Environmental Assessment of Biomass Conversion to Synthetic Fuels, PB 289775 (Battelle-Columbus Laboratories, 1978).

Reactivity and Gasification Characteristics of Low Ranking Coals and Potentially Reducing Waste Materials, PERC/RI-76/2 (Pittsburgh Energy Research Center, 1976).

Reed, T. and B. Bryant, *Densified Biomass: A New Form of Solid Fuel*, SERI-35 (Solar Energy Research Institute, 1978).

Revised Energy Conservation Investment Program Guidance (DA, April 1977).

Schanche, G., S. A. Hathaway, and J. Oxley, *Technical and Economic Guide for Air Pollution Control Systems*, Draft Technical Report (CERL).

Shafizadeh, F. and W. DeGroot, "Thermal Analysis of Forest Fuels," *Fuels and Energy from Renewable Resources* (Academic Press, 1977).

Smith, M. and K. Stinson, *Fuels and Combustion* (New York, 1952)

Solid Fuel Burners (Peabody Gordon-Piatt, Inc., 1979).

Spurr, Stephen H., "Silviculture," *Scientific American*, Vol 240, No. 2 (1979).

Steam (Babcock and Wilcox, Inc., 1975).

Stokers for Industrial Boilers — Assessment of Technical, Economic, and Environment Factors, PB288689 (Battelle-Columbus Laboratories, 1975).

Study of Alternate Fuels, Heating Plant for Major Support Area, Trident Submarine Base, Bangor Annex, Keyport, Washington (Bumstead-Woolford, Co., 1978).

Supplemental Wood Fuel Experiment (Board of Light and Power, Grand Haven, MI, 1978).

Tillman, D. *Wood as an Energy Resource* (Academic Press, 1978).

Tuttle, K. and D. Junge, "Combustion Mechanisms in Wood Fired Boilers," *Journal of the Air Pollution Control Association*, Vol 28, No. 7 (July 1978).

West, B. and J. Woodyard, *Assessment of Dry Granular Media Scrubbers for Abatement of Particulate Emissions From Stationary Point Combustion Sources on Army Fixed Facilities and Installations* (SCS Engineers, Long Beach, CA, 1979).

Wilson, D. G., *Handbook of Solid Waste Management* (Van Nostrand-Reinhold, 1978).

Wood Energy for Small Scale Power Production in North Carolina (Ultrasystems, Inc., 1978).

APPENDIX A:*
WOOD PELLET BIN AND
FEEDER DESIGN

Introduction

The Army Corps of Engineers is in the process of designing a storage bin to handle a form of pelletized sawdust called Woodex. The Woodex, consisting of pellets ½ to 2 in. long, will be blended with coal and burned. A storage capacity of 250 tons or approximately a 3 days' supply is required.

Jenike and Johanson, Inc. was asked to test the material to determine its flow properties and design a bin to provide reliable material flow and to prevent any serious degradation of the pellets during storage and handling.

Material Properties

Tests were run to simulate continuous flow and the effect of 3 days' storage at rest at ambient temperature. In addition, wall friction angles and a density-pressure relationship were determined.

The Woodex pellets are easily crushed, and a significant amount of fines accompanies the pellets. Consequently, the tests were run on the minus 8 mesh fraction of the pellets to provide conservative design values. The Woodex fines are capable of forming large stable ratholes in funnel flow bins; therefore, mass flow is necessary to prevent ratholing and provide reliable flow. Two main considerations for mass flow are the size of the outlet required to prevent a stable arch from forming and the smoothness and steepness of the hopper walls to allow material to flow along them.

On a continuous flow basis, as well as after 3 days' storage at rest, the outlet dimensions required to prevent a stable arch from forming are essentially zero. Instead, the outlet size is set by consideration of particle interlocking, etc. As a rule of thumb for setting the outlet size based on particle interlocking, a value of four times the largest particle size determines the slot width, and eight times the largest particle size determines the conical diameter.

Wall friction tests were run on samples on aged carbon steel and 304 stainless steel with a 2B finish.

As mentioned previously, an important factor in mass flow is that material slides along the wall. Aged carbon steel does not provide a smooth enough surface for material to slide on, whereas 304 stainless steel with a 2B finish provides an excellent surface for siding. Although after 3 days' storage at rest, the material will have a tendency to adhere to the stainless, it is still much better than the aged carbon steel.

An additional test was run on whole pellets to determine the amount of consolidating pressure that the Woodex would withstand before crushing. It was determined that pellets began to chip and break at approximately 350 psf and particles also began to crush at approximately 850 psf. This is an equivalent head of about 11 and 27 ft, respectively.

Recommendations

Because of the sensitivity of the Woodex to crushing, the bins must be designed to limit the effective head on the pellets to 20 ft or less. We recommend that the bins shown in Figure A1 be used to minimize crushing and provide reliable flow. This bin is divided into two parts with belt feeders (Figure A2) to draw material uniformly from the bin feeding it to a common collecting belt conveyor, as shown in Figure A3. The belt feeders may be enclosed to control dusting.

General Comments — Feeder Loads

The force on that portion of the belt feeder which is under the bin outlet can be resolved into a normal (vertical) and shear (horizontal) component:

   normal load = 39 F + 92 lb
   shear load = 45 F lb

where F is a dimensionless multiplier depending on flow conditions in the hopper.

1. Normal Operation

   a. Normal running of the feeder   F = 1.0

   b. The feeder is restarted after it has been running. No material was added to the bin while the feeder was stopped.   F = 1.0

2. Initial Startup — Feeder Supported From Hopper. This arrangement eliminates differential deflection between the hopper and feeder.

a. The bin has a head of at least 20
of material in it. The feeder is
stopped while the bin is refilled.
At startup,   F = 1.2

b. The bin is empty. It is then
refilled and the feeder is run
at a slow rate during filling.
When the feeder is first
increased to full-speed,   F = 1.2

c. The bin is empty. It is then
refilled while the feeder
remains stopped. At startup,   F = 2.5

3. Initial Startup—Feeder and Hopper Independently Supported. This allows significant differential deflection between the feeder and hopper.

a. The bin is empty. It is then
refilled and the feeder is run at
a slow rate during filling. When
the feeder is first increased to
full speed operation,   F = 1.2

b. The bin is empty. It is then
refilled without running the
feeder. At startup,   F = 3.0 + *

c. Elastic supports are provided
for the feeder. At startup.   F = 1.5

The elastic supports should be designed to maintain the feeder in its proper position while running. This can also be accomplished by mounting the feeder on hydraulic or pneumatic cylinders which are designed to normally hold the feeder in its maximum vertical position. If starting problems occur, the pressure in the cylinders is reduced to allow the feeder to deflect. Then, when the feeder is running, the pressure is gradually increased to raise the feeder to its usual maximum height.

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*This factor depends on the relative deflection of the bin and feeder, the compressibility of the solid, and the clearance between the feeder and bin.

total volume = 18,000 cu. ft
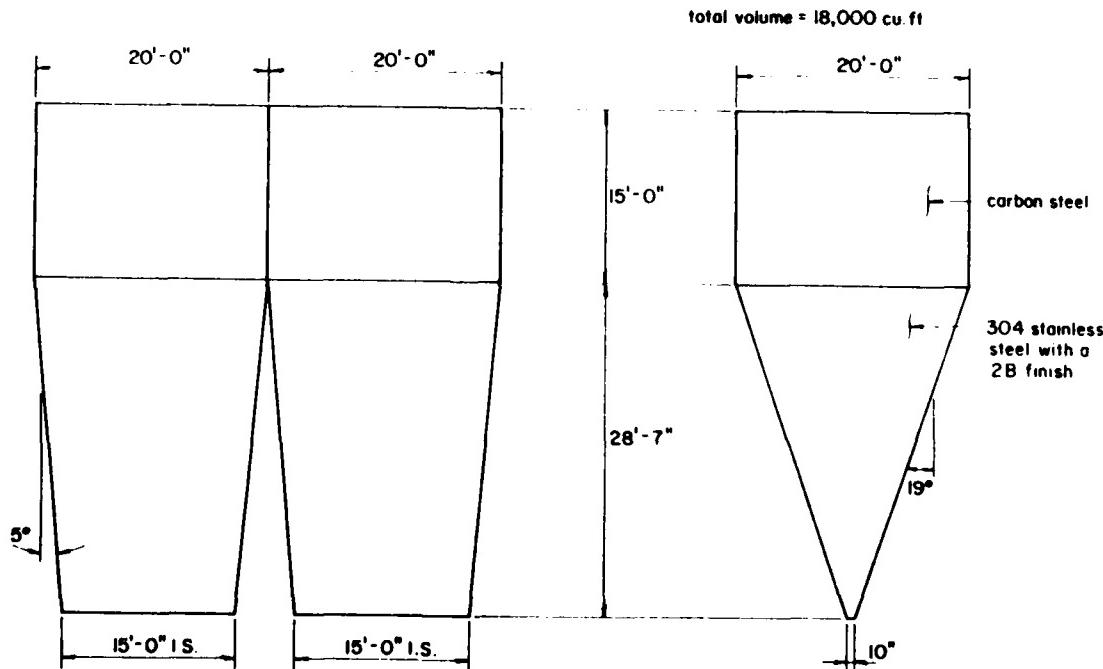
Figure A1. Modular bin design.

x, ft	0	3	6	9	12	15
G, in	0.5	1.8	3.0	3.9	4.8	5.6

73/4"

bottom flange

6"

10" I.S.

PLAN VIEW

hopper

6 3/8"

5 5/8"

45°

6 3/8"

T/O 24" belt w/45°
equal length troughing
idlers.

A

2'-2 1/2"

x

G

15'-2" I.S.

304-2B
stainless steel

10"

10°

B

45°

9"

**Countersink
bolts flush**

DETAIL B

bar or washers

rubber skirt

bottom of steel

3"
typ

1"

1/2"

DETAIL A
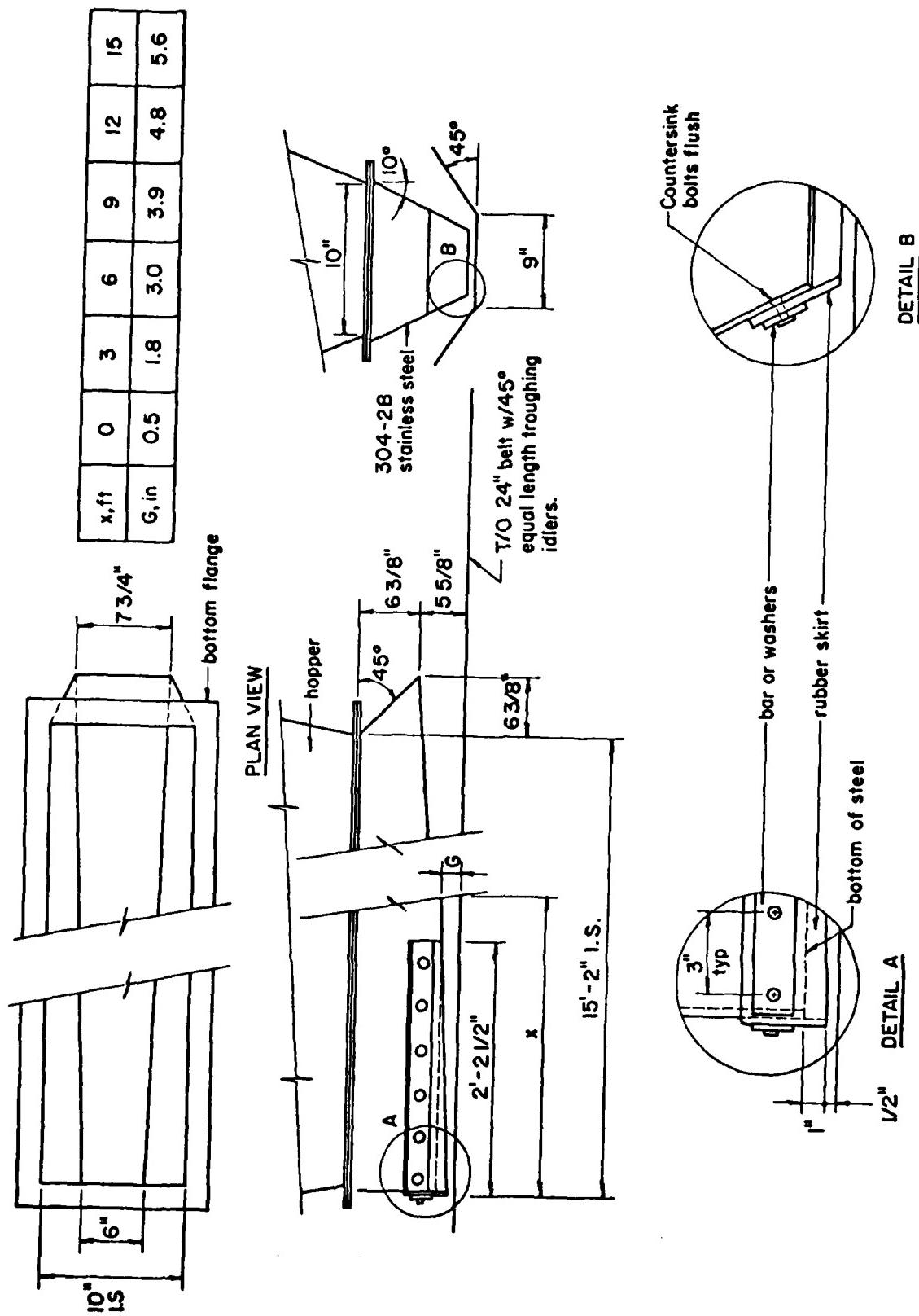
Figure A2. Bolt feeder design.

Interior Surface Finish

Whenever possible, welding should be done on the outside of the hopper. If interior welding is necessary, all welds on sloping surfaces must be ground smooth and power brushed to retain a smooth surface. After welding, all sloping surfaces must be clean and free of weld spatter.

The surface finish is most critical in the region of the hopper outlet; therefore, any blisters in this area from exterior welding must be brushed smooth. Horizontal or diagonal welded connections should preferably be lapped with the upper section on the inside so that the resulting ledge does not impede flow. If horizontal butt welds are used, care must be taken to avoid any protrusion into the flowing solid. Vertical welds coinciding with the direction of material flow can be either butted or lapped without causing flow problems, providing they are ground smooth and power brushed as noted above.

Mating Flanges

The lower of two mating flanges must be oversized to prevent any protrusions into the flowing solid. The amount of oversize depends on the accuracy of the construction and erection; usually 1 m overall is sufficient.

All flanges should be attached to the outside of the hopper, with the hopper wall material being the surface in contact with the flowing solids. This insures that the flange does not protrude into the flowing solids emptying the bin.
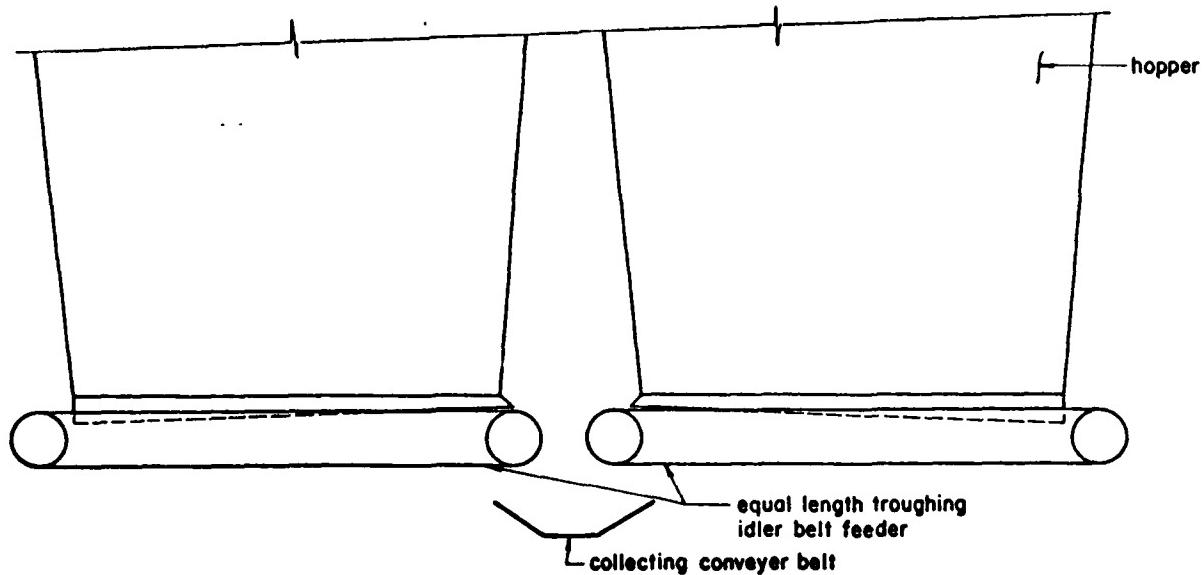

Figure A3. Belt feeder configuration.

APPENDIX B:*
LABORATORY ANALYSES OF
WOOD PELLETS

Introduction

The flow properties of the material tested are expressed in terms of bin dimensions required to insure dependable flow, maximum hopper angles for mass flow, and, if tested, minimum chute angles and critical discharge rates through bin outlets. All dimensions represent limiting conditions for flow. Therefore, larger outlets, steeper hoppers and chutes, and flow rates below critical are acceptable. If the material is one which will compact excessively in a large bin, the largest diameter or width and height of the cylinder to limit this compaction is also given.

The Annex to this Appendix explains the type of data discussed here. Most of the symbols used in this Appendix are shown in Figures 1B1, 1B2, and 1B3 of the Annex. A Glossary of Terms and Symbols is also provided in the Annex.

*These data were prepared by Jenike and Johanson, Inc., North Billerica. MA.

Comments

In order to maintain a conservative bin design, only the minus 8 mesh fraction of Woodex pellets was tested.

The Woodex is capable of forming large stable ratholes in funnel flow bins; therefore, mass flow is a more reliable means of handling it. In a mass flow bin, the outlet dimensions needed to prevent a stable arch from forming are small for both continuous flow and for 3 days' storage at rest at ambient temperature.

Wall friction tests on samples of aged carbon steel and 304 stainless steel with a 2B finish were run. The stainless provided a good sliding surface for the materials. Crushing tests were also run and showed that the Woodex is sensitive to the consolidating pressures that may occur during storage.

Tables B1 through B6 provide the results of the tests conducted on Woodex 8 mesh, moisture content 9.0 percent.

Figures B1 through B9 are graphs providing data from some of the testing results.

Table B1
Bin Dimensions (0.0 Hours Storage Time)
Material: Woodex

Particle Size 100 Percent—8 Mesh
Moisture Content 9.0 Percent

Bin Dimensions for Dependable Flow (in feet)
Storage Time at Rest: 0.0 hour
Temperature: 72°F
Bins With Unlimited Maximum Size

	Mass Flow				**Funnel Flow**					
P-FACTOR	BC*	BP	BF	EH =	2.5	5	10	20	40	52
1.00	0.+	0.+	0.*	DF =	0.0	2.0	11	29	63	83
1.25	0.+	0.+	0.*	DF =	0.0	4.4	15	37	78	103
1.50	0.+	0.+	0.*	DF =	0.0	7	19	44	94	124
2.00	0.+	0.+	+	DF =	1.5	11	27	60	124	163

*See Glossary of Terms and Symbols for definition of abbreviations used throughout this Appendix.

0.+ Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

+Denotes a dimension larger than 19.6 ft.

Table B2
Bin Dimensions (65.0 Hours Storage Time)
Material: Woodex

Particle Size 100 Percent — 8 Mesh
Moisture Content 9.0 Percent

Bin Dimensions (in feet) for Dependable Flow
Storage Time at Rest: 65.0 hours
Temperature: 72°F
Bins With Unlimited Maximum Size

	Mass Flow				**Funnel Flow**					
P-FACTOR	BC	BP	BF	EH =	2.5	5	10	20	40	52
1.00	0.*	0.*	0.*	DF =	0.0	2.4	11	27	59	78
1.25	0.*	0.*	0.*	DF =	0.0	4.6	15	35	74	97
1.50	0.*	0.*	0.*	DF =	0.0	7	19	42	89	116
2.00	0.*	0.*	+	DF =	1.9	10	26	56	117	154

0.*Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be
   selected by consideration of particle interlocking, flow rate, etc.

+Denotes a dimension larger than 18.5 ft.

Table B3
Bulk Density
Material: Woodex

Particle Size 100 Percent — 8 Mesh
Moisture Content 9.0 Percent

Bulk Density

Temperature: 72°F

EH, ft	0.5	1.0	2.5	5.0	10.0	20.0	40.0	80.0
SIGMA1, psf	12.	25.	67.	141.	297.	623.	1308.	2746.
GAMMA, pcf	24.0	25.2	26.9	28.2	29.7	31.1	32.7	34.3

Compressibility Parameters:

Bulk density, GAMMA, is a function of the principal consolidating pressure SIGMA1, as follows:

$$GAMMA = GAMMA0 \ (SIGMA1 \ / \ SIGMA0)^{BETA}$$

For GAMMA between 26.4 and 34.4 pcf,

   GAMMA0 = 24.1 pcf

   SIGMA0 = 13.0 psf

   BETA = 0.06580

GAMMA MINIMUM = 23.7 pcf

Table B4
Aged Carbon Steel (0.0 Hours Storage Time at Rest)

Material: Woodex

Particle Size 100 Percent – 8 Mesh
Moisture Content 9.0 Percent

Maximum Hopper Angles for Mass Flow

Wall Material: Aged Carbon Steel

Storage Time at Rest: 0.0 hour

Temperature: 72°F

Hopper Angles for Various Hopper Spans

	0.25	0.5	1.0	2.0	4.0	5.0	16.2
Width of Oval, ft	0.25	0.5	1.0	2.0	4.0	5.0	16.2
Dia of Cone, ft	0.5	1.0	2.0	4.0	8.0	10.0	32.3
Wall Friction Angle							
PHI-PRIME, deg	44.	42.	34.	31.	30.	30.	29.
Hopper Angles							
THETA-P, deg	7.	10.	18.	20.	21.	21.	22.
THETA-C, deg	0.	0.	6.	9.	10.	11.	12.

Note: Flow along walls is questionable for oval widths less than 0.44 ft and conical diameters less than 0.88 ft.

Table B5
304-#2B Stainless Steel (0.0 Hours Storage Time at Rest)

Material: Woodex

Particle Size 100 Percent – 8 Mesh
Moisture Content 9.0 Percent

Wall Material: 304-#2B Stainless Steel

Storage Time at Rest: 0.0 hour
Temperature: 72°F

Hopper Angles for Various Hopper Spans

	0.25	0.5	1.0	2.0	4.0	5.0	16.2
Width of Oval, ft	0.25	0.5	1.0	2.0	4.0	5.0	16.2
Dia of Cone, ft	0.5	1.0	2.0	4.0	8.0	10.0	32.3
Wall Friction Angle							
PHI PRIME, deg	27.	21.	19.	18.	17.	16.	14.
Hopper Angles							
THETA-P, deg	27.	32.	35.	36.	37.	37.	40.
THETA-C, deg	14.	20.	22.	24.	25.	26.	28.

Note: Flow along walls is questionable for oval widths less than 0.12 ft and conical diameters less than 0.24 ft.

Material: Woodex

Particle Size 100 Percent – 8 Mesh
Mosture Content 9.0 Percent

Wall Material: 304-#2B Stainless Steel
Storage Time at Rest: 65.0 hours
Temperature: 72°F

Hopper Angles for Various Hopper Spans

Width of Oval, ft	0.25	0.5	1.0	2.0	4.0	5.0	11.4
Dia of Cone, ft	0.5	1.0	2.0	4.0	8.0	10.0	22.7
Wall Friction Angle							
PHI-PRIME, deg	55.	40.	34.	24.	19.	18.	16.
Hopper Angles							
THETA-P, deg	7.	7.	19.	29.	33.	35.	38.
THETA-C, deg	0.	0.	6.	17.	22.	23.	26.

Note: Flow along walls is questionable for oval widths of less than 0.76 ft and conical diameters of less
than 1.53 ft.
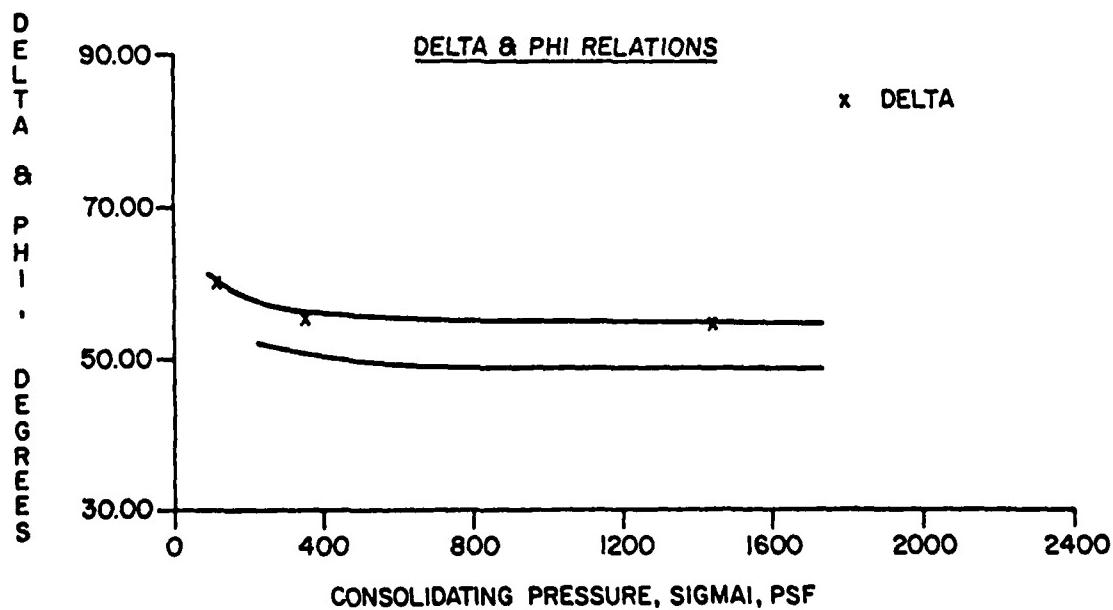
Figure B1. Delta and phi vs. consolidating pressure

FLOW FUNCTION(S)

x   0.0 HR TEMP 72°F
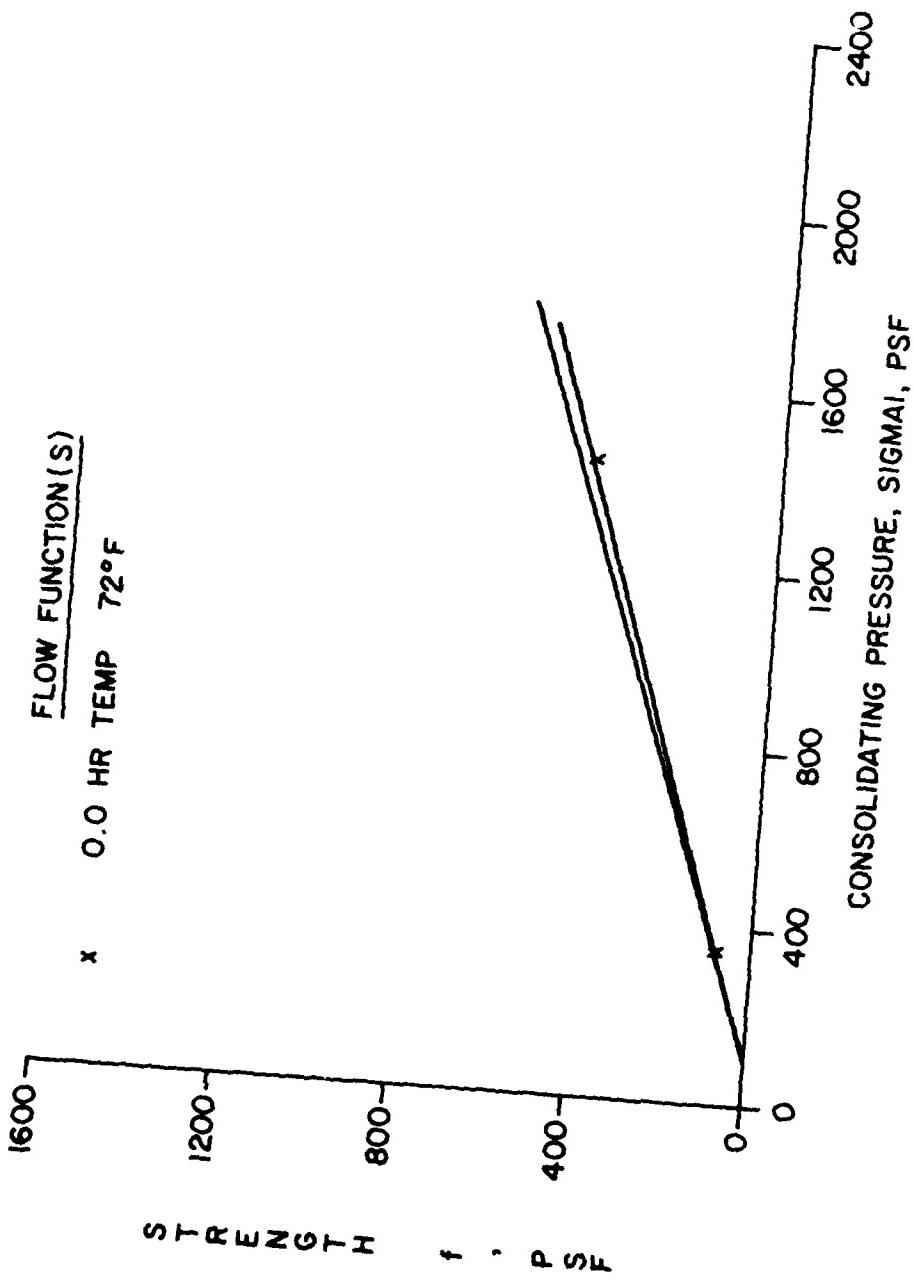
Figure B2. Strength vs. consolidating pressure.

YIELD LOCUS

↑ STEADY STATE
x   0.0 HR TEMP 72°F
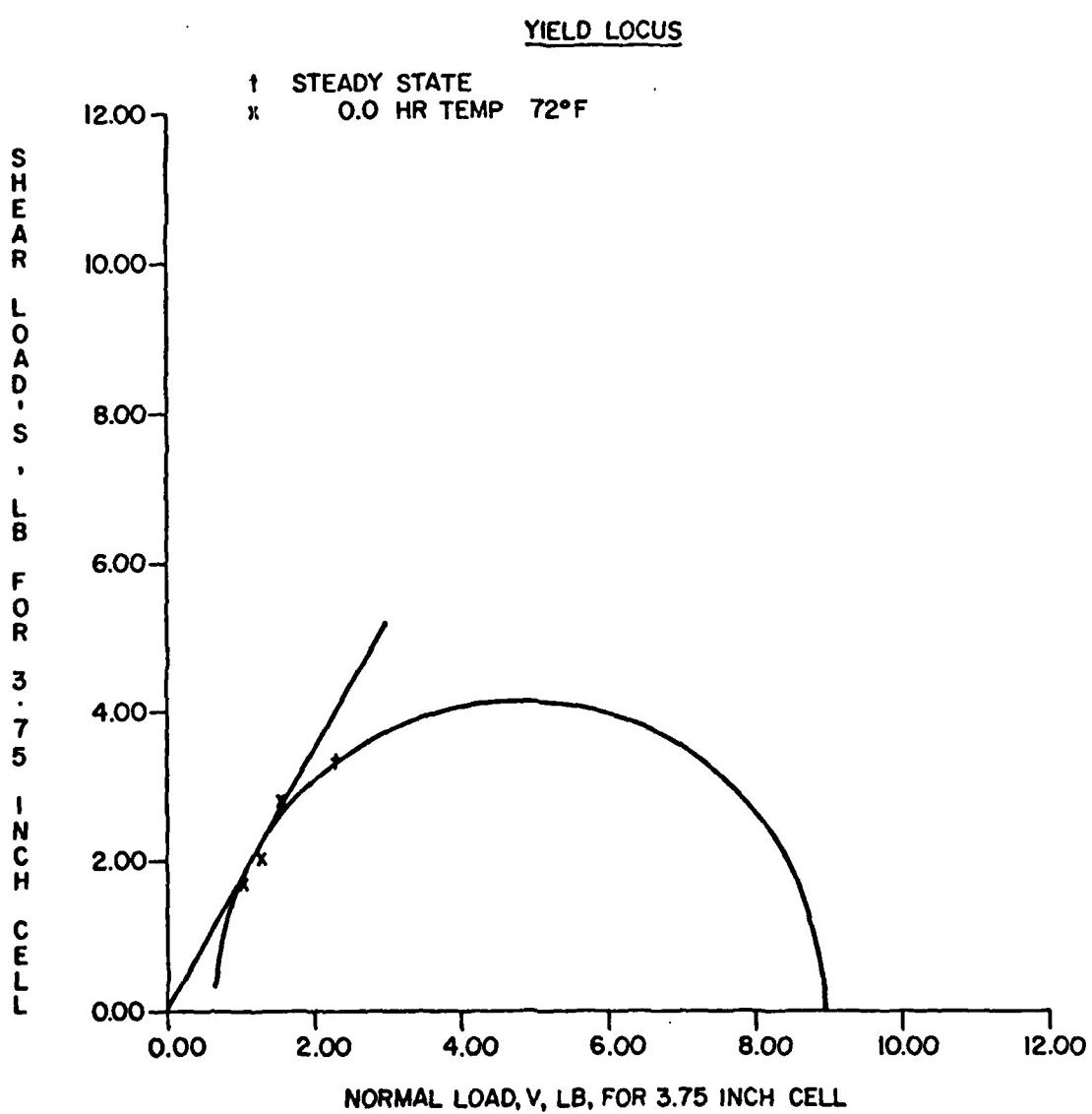
Figure B3. Shear load vs. normal load for 3.75-in. cell (0.00 to 12.00 lb).

YIELD LOCUS
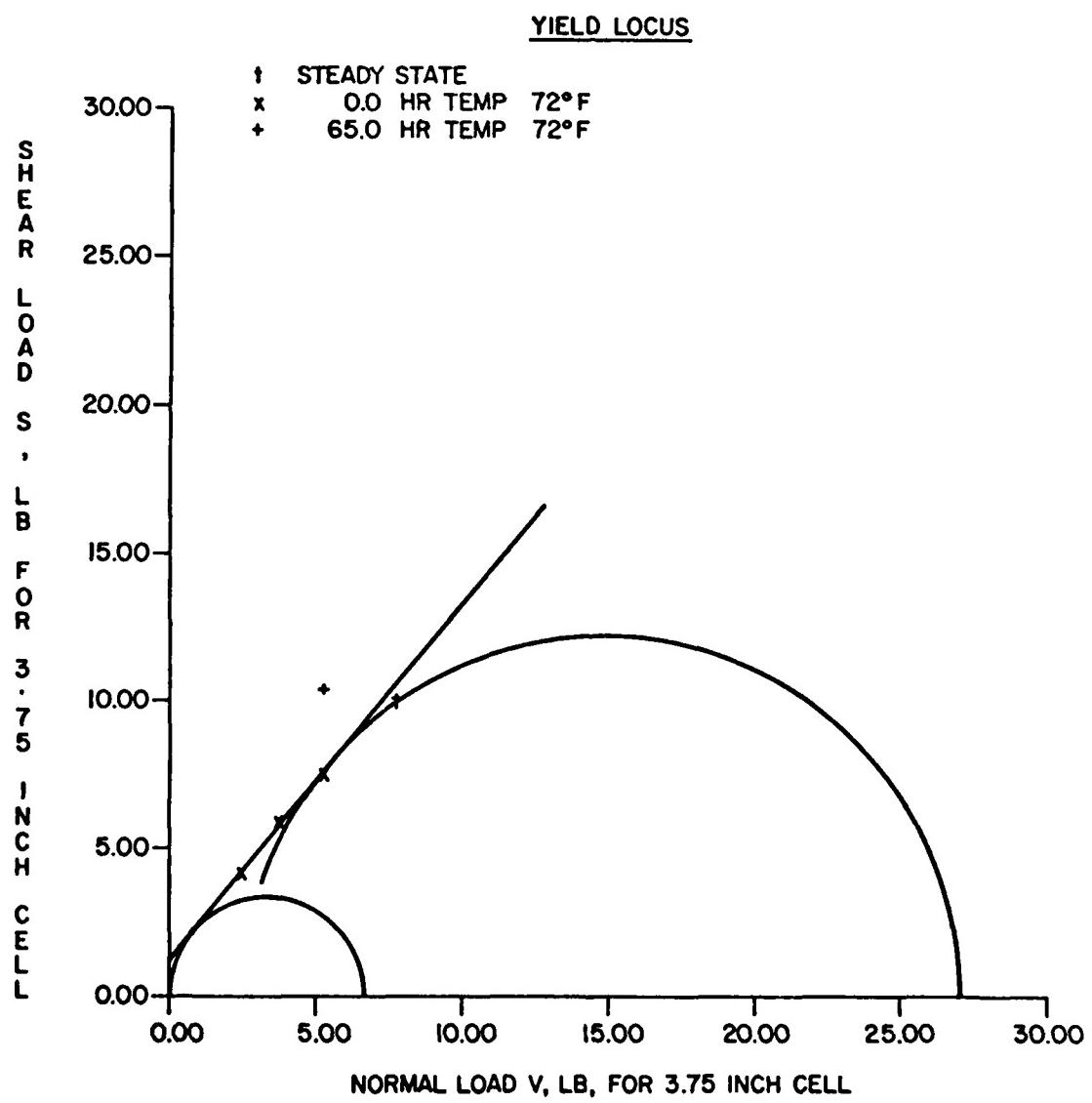
**Figure B4.** Shear load vs. normal load for 3.75-in. cell (0.00 to 30.00 lb).

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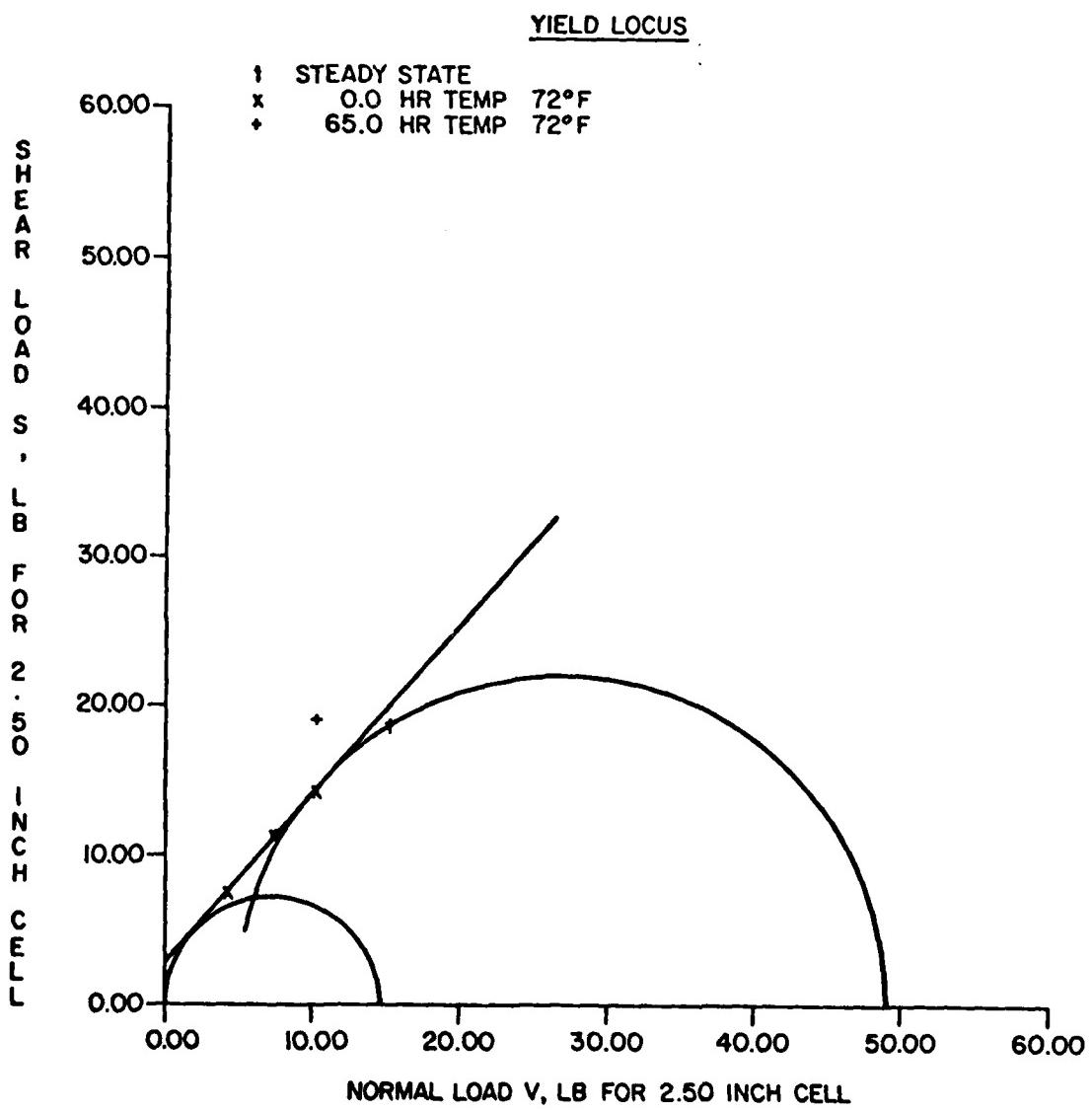
Figure B5. Shear load vs. normal load for 2.50-in. cell (0.00 to 60.00 lb).

LOG GAMMA VS. LOG CONSOLIDATING PRESSURE RELATION

TEMPERATURE 72° F
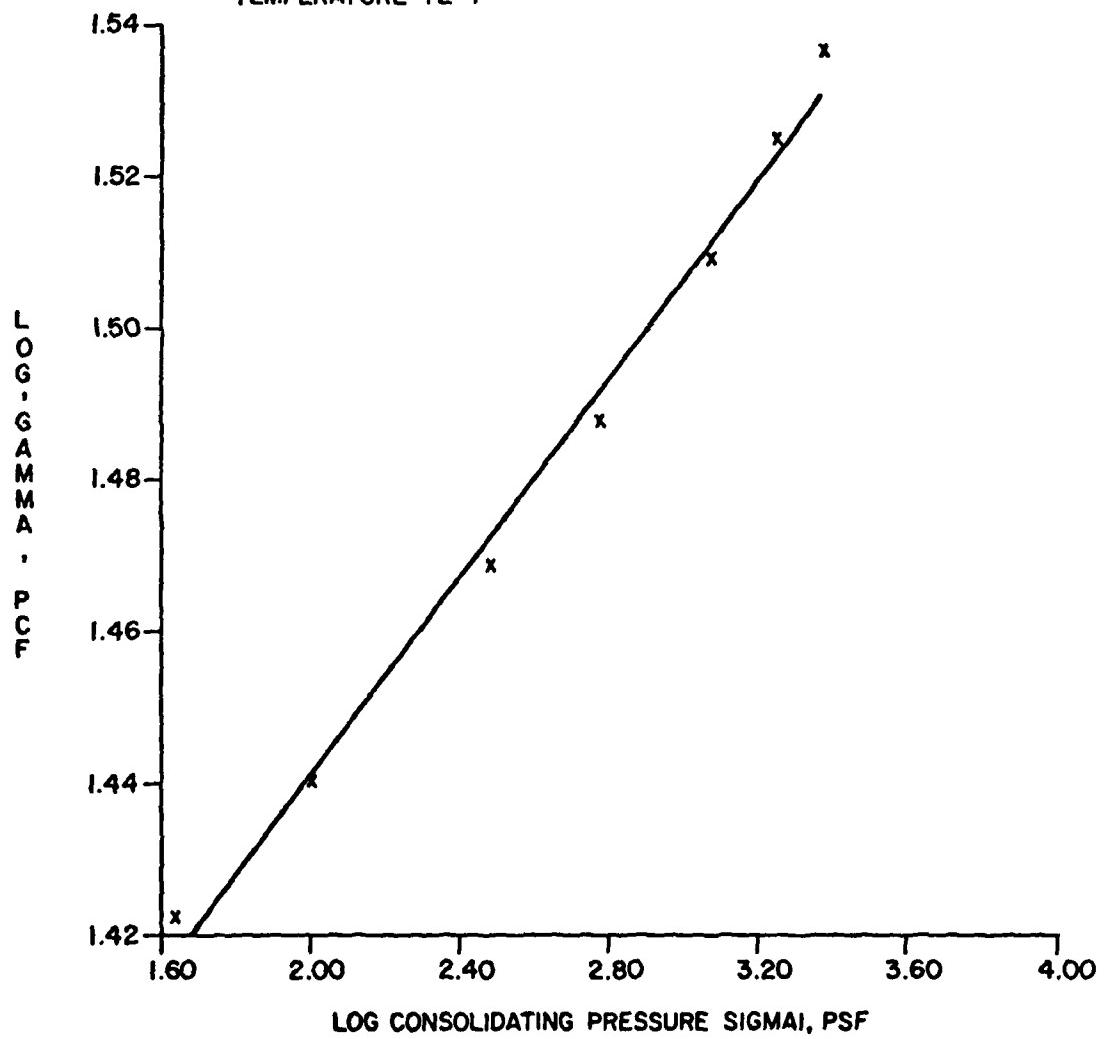
Figure B6. Log vs. log consolidating pressure.

70
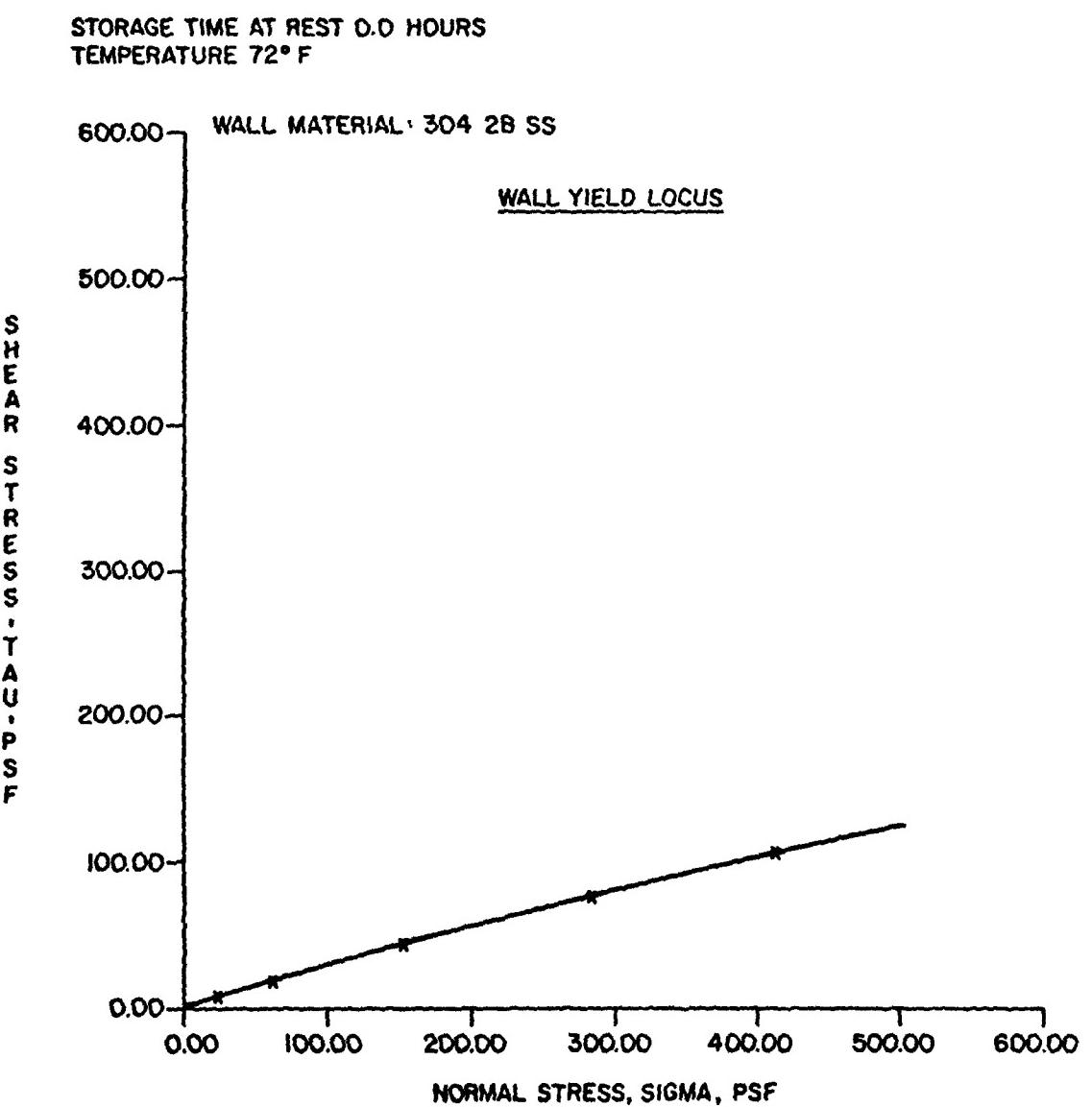
Figure B7. Shear stress vs. normal stress — 304 2B SS (0.00 to 600.00 psf).

STORAGE TIME AT REST 65.0 HRS.
TEMPERATURE 72° F

WALL MATERIAL : 304 2B SS

WALL YIELD LOCUS
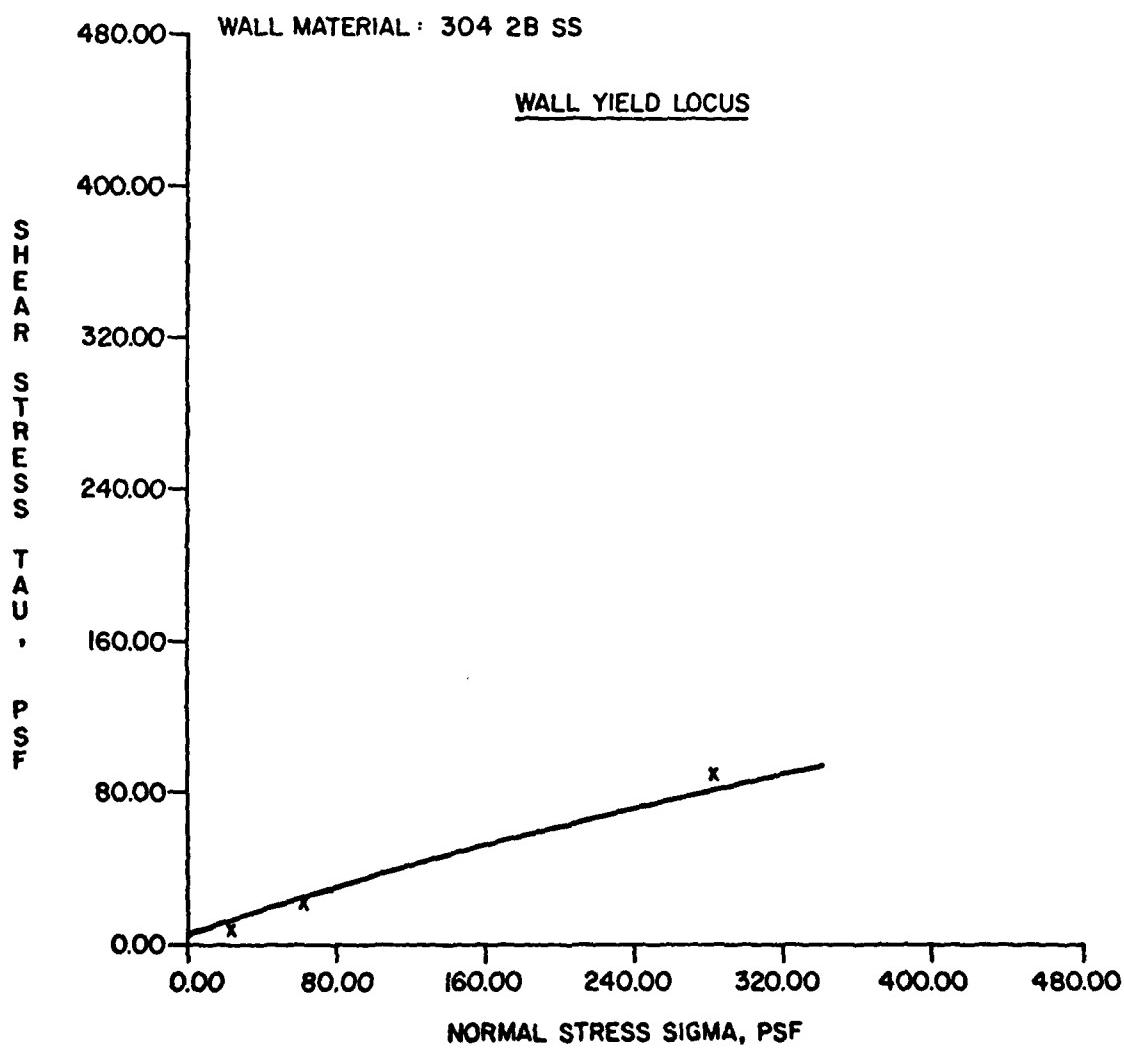
Figure B8. Shear stress vs. normal stress — 304 2B SS (0.00 to 480.00 psf).

STORAGE TIME AT REST 0.0 HRS.
TEMPERATURE 72°F

WALL MATERIAL: AGED CARBON STEEL

WALL YIELD LOCUS
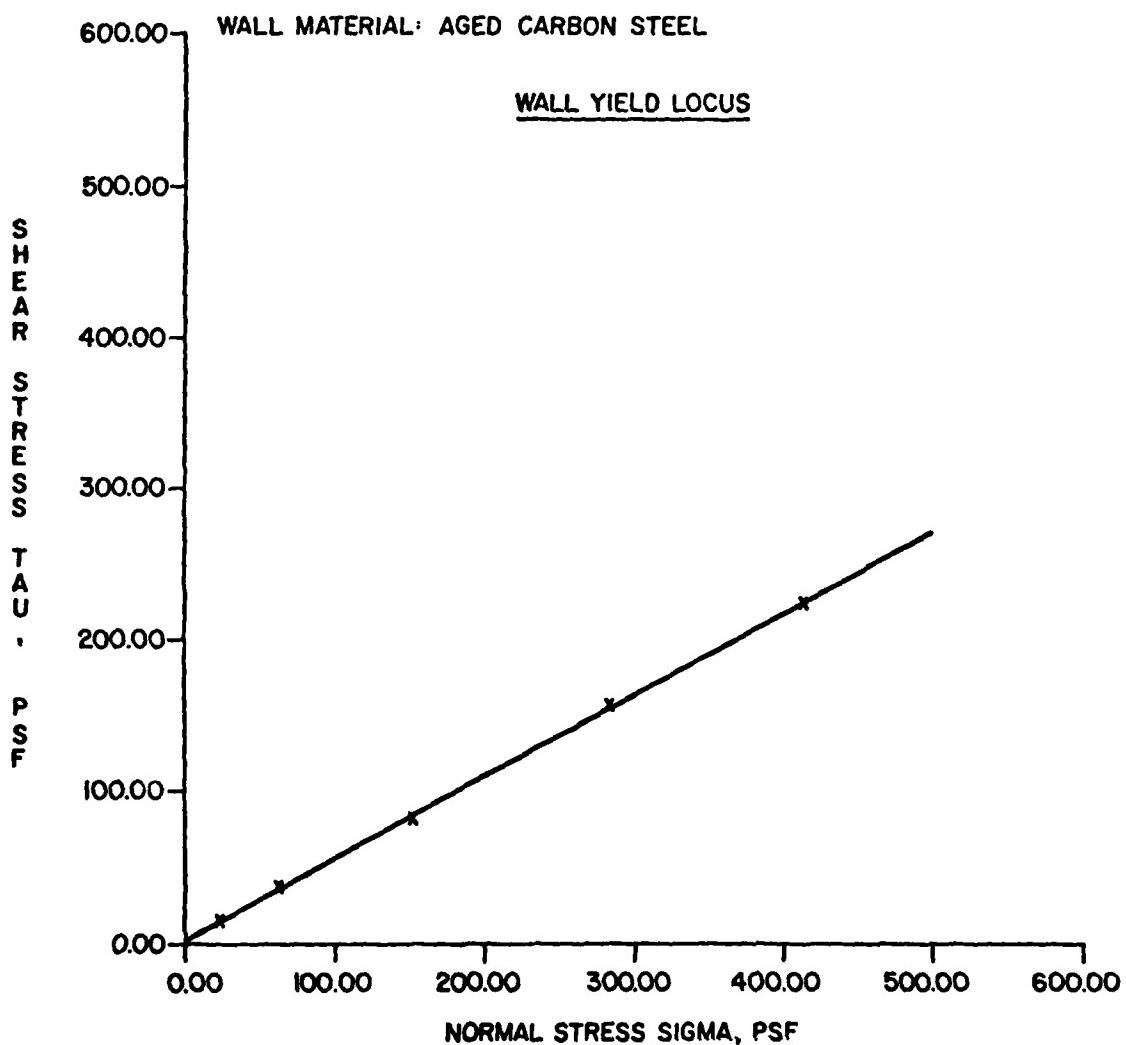
Figure B9. Shear stress vs. normal stress—aged carbon steel (0.00 to 600.00 psf).

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ANNEX 1: TEST DATA

Selection of Bin and Feeder

Types of Bins

A bin (silo, bunker) generally consists of a vertical cylinder and a sloping, converging hopper. The first step in selecting a bin is to decide on the type required. From the standpoint of flow, there are three types: mass-flow, funnel-flow, and expanded-flow.

Mass-Flow Bins. In mass-flow bins, the hopper is steep and smooth enough to allow flow of all the solid and yet prevent the formation of stagnant regions when any of the solid is withdrawn.

Mass-flow bins (see Figure 1B1) have certain advantages. Flow is uniform, and the feed density is practically independent of the head of solid in the bin, which often permits the use of volumetric feeders for controlling feed rate. Low-level indicators work reliably. In addition, segregation is minimized because, while a solid may segregate at the point of charge into the bin, the first-in/first-out flow sequence forces the same particle size distribution to exit from the hopper that entered it. This flow sequence also insures uniform residence time and de-aeration of a fine powder. Hence, air locks often need not be used, provided the critical in-flow and out-flow rates are not exceeded.

Valleys, ledges, and protrusions are not permitted in the hopper. In addition, the outlet must be fully effective, i.e., if the hopper is equipped with a shut-off gate, the gate must be fully open; if it is equipped with a feeder, the feeder must draw material across the full outlet area.

Mass-flow bins are recommended for cohesive materials, for materials which degrade with time, for powders, and when segregation must be minimized. Mass-flow bins of special design can be used to blend the contents of the bin by circulating the stored solid.

Funnel-Flow Bins. Funnel-flow occurs when the hopper is not steep and smooth enough to force material to slide along the walls or when the outlet of a mass-flow bin is not fully effective. Examples of funnel-flow bins are shown in Figure 1B2.

In a funnel-flow bin, solid flows toward the outlet through a channel that forms within stagnant mate-

rial. The diameter of that channel approximates the largest dimension of the effective outlet. When the outlet is fully effective, this dimension is the diameter of a circular outlet, or the diagonal of a square or slotted (rectangular) outlet. Powders withdrawn at a high flow rate from a funnel-flow bin may remain fluidized due to the short residence time in the flow channel and flush on exiting the bin.

As the level of solid within the channel drops, layers slough off the top of the stagnant mass into the channel. This spasmodic behavior is particularly detrimental with cohesive solids, since the falling material packs, thereby increasing the chance of arching. A channel, especially a small high-velocity channel, may empty out completely (rathole), and powder charged into the bin then flushes through. Under these conditions, a rotary valve is often used to contain the material, but a uniform flow rate cannot be insured because flow into the valve is erratic.

Since funnel-flow bins are more likely to cause arching of cohesive solids than mass-flow bins, they usually require larger outlets to achieve dependable flow. These bins also segregate solids and are unsuitable for solids which degrade with time in the stagnant regions. Cleanout of a funnel-flow bin is often uncertain, because solid in the stagnant regions may pack and cake.

Funnel-flow bins are only suitable for coarse, free-flowing, or slightly cohesive, nondegrading solids when segregation is unimportant.

Expanded-Flow Bins. Examples of expanded-flow bins are shown in Figure 1B3. The lower part of this type of bin operates in mass-flow. The mass-flow outlet usually requires a smaller feeder than would be used for a funnel-flow bin. The mass-flow hopper should expand the flow channel to a diagonal or diameter equal to or greater than the critical rathole diameter, thus eliminating the likelihood of ratholing.

These bins are recommended for storing large quantities of nondegrading solids. This design is also useful as a modification of existing funnel-flow bins to correct erratic flow caused by arching, ratholing, or flushing.

The concept can be used with multiple outlets as shown in Figure 1B3 (b) where simultaneously flowing mass-flow hoppers are close enough together to cause

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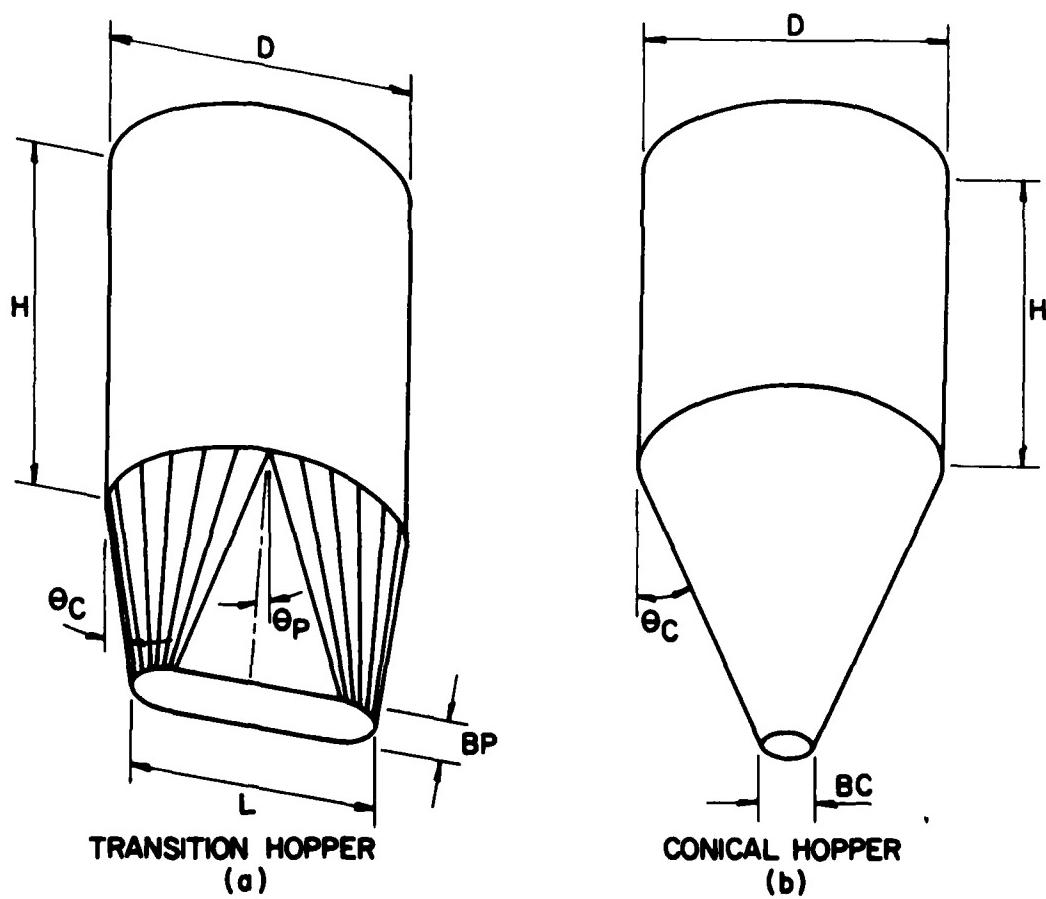
Figure 1B1. Mass flow bins.

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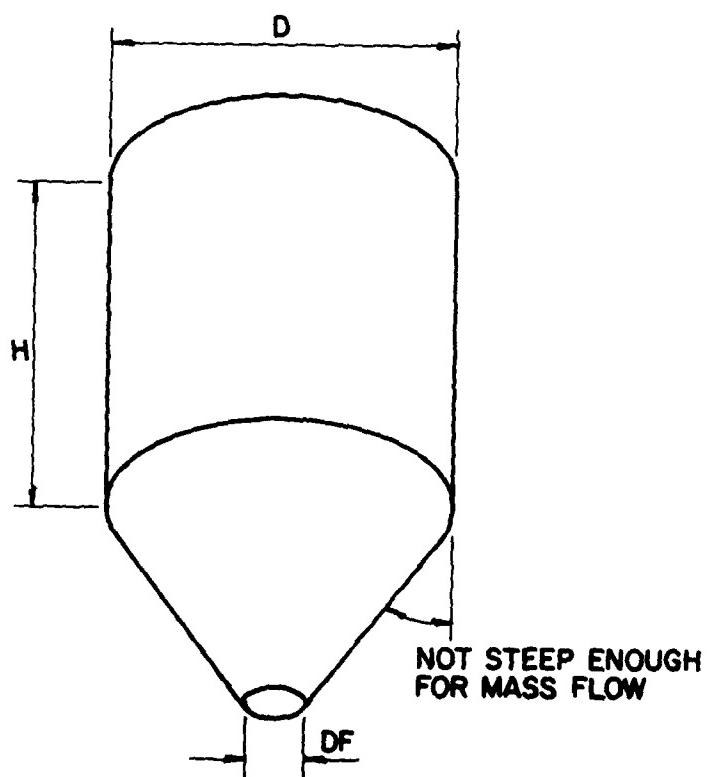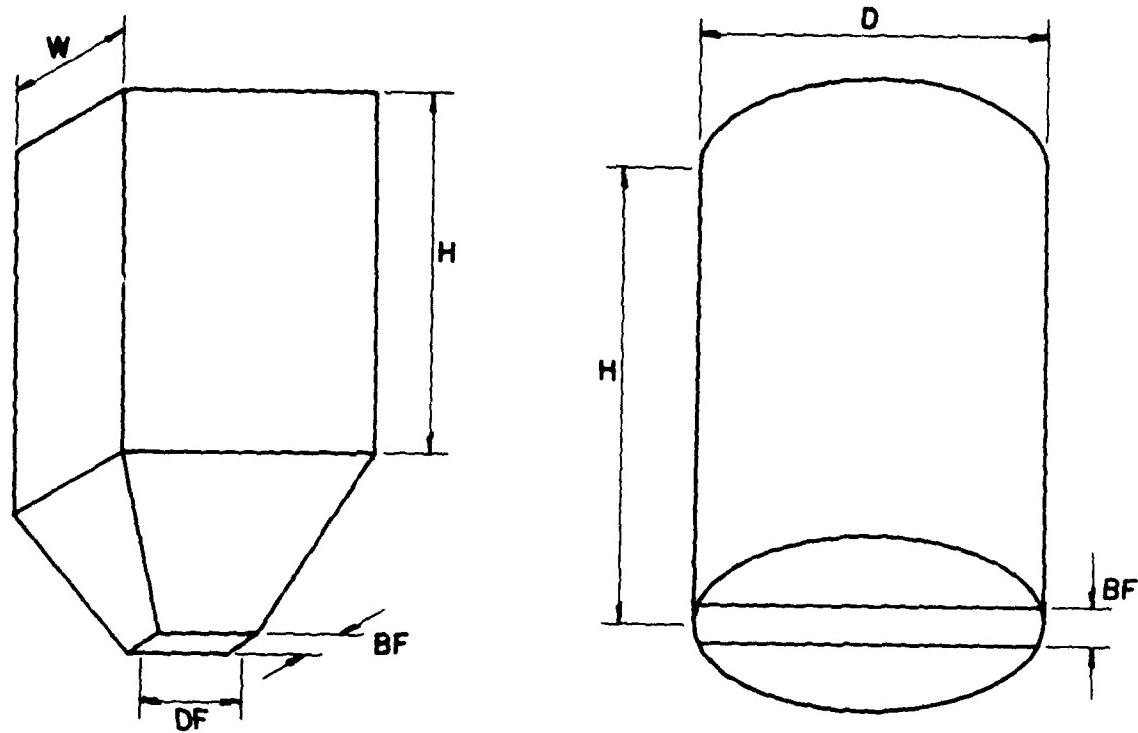
Figure 1B2. Funnel flow bins.
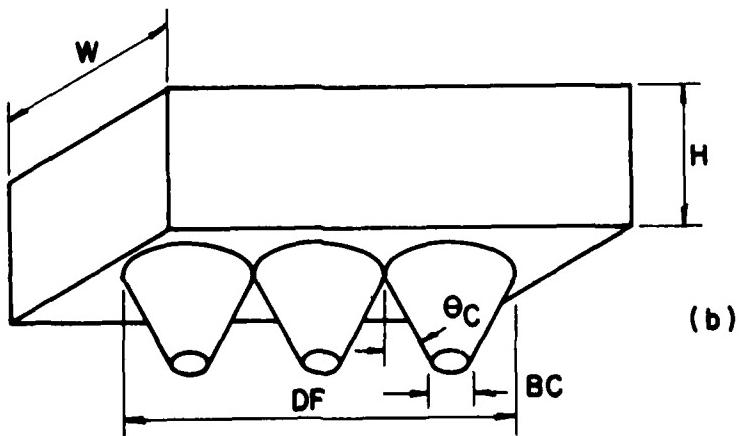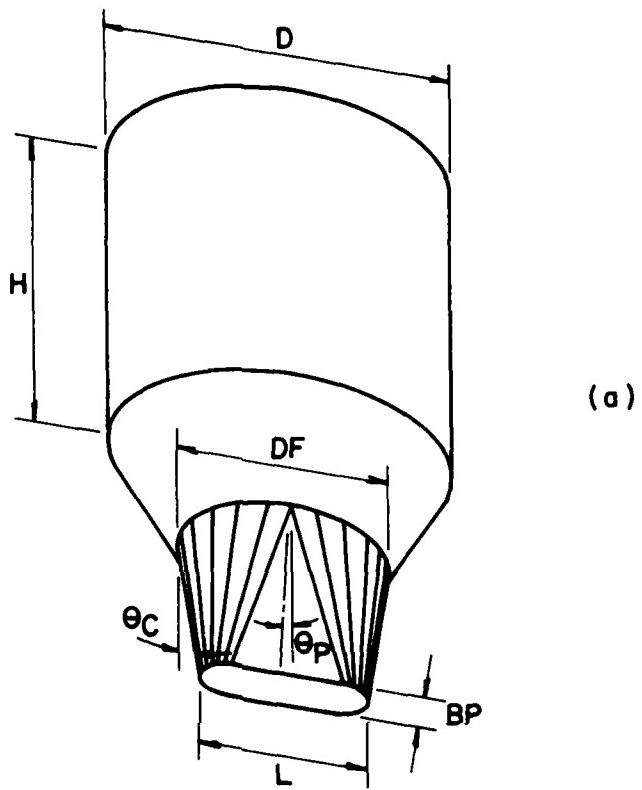
Figure 1B3. Expanded flow bins.

a combined flow channel that exceeds the critical rathole diameter.

Feeders

The specified outlet must be fully effective. If flow from the bin is controlled by a feeder, the feeder must be designed to draw uniformly through the entire cross-section of the outlet, a condition which few commercially available feeders satisfy.

This is especially important when feeding fine powders from long slotted outlets (L>3B). Typical commercial designs tend to draw material either from the front or the back of the slot, resulting in a high-velocity channel having a diameter of one to two times the width of the outlet. The powder may remain fluidized within this channel and flush on exiting the bin.

To limit high initial loads and starting torque, it is essential that the feeder either be suspended from the bin itself or supported on a flexible frame so as to readily deflect with the bin as solid is added to it. When the feeder is properly designed for uniform flow, and when convergence of the hopper extends to the feeder, the effective head (EH) of solid on the feeder during flow in a mass flow bin will then be approximately

$$EH = BP \text{ for a transition hopper}$$

$$EH = BC/2 \text{ for a conical hopper}$$

[Eq 1B1]

Vibrating Equipment

Vibration has two effects: (1) it tends to break arches that obstruct flow, and (2) it packs the solid in stagnant regions, thereby giving it greater strength. To allow for this packing, the recommended outlet dimensions at zero time at rest for a P-FACTOR (described below) of 1.5 may generally be used.

Vibrators are suitable for materials which are free-flowing under conditions of continuous flow but which cake and gain strength when stored at rest for hours or days. Hoppers for these materials should be equipped with pads for mounting external vibrators. Vibrating equipment is generally not recommended for fine powders and wet materials since they tend to pack severely when vibrated.

Discussion of Test Report Data

In the following discussion, each Section of the test report is explained in general terms. Refer to Figures 1B1, 1B2, and 1B3, where many of the symbols are shown. The symbols and other terms used in the text are defined in the Glossery of Terms and Symbols.

Section 1 — Bin Dimensions for Dependable Flow

This section specifies the bin dimensions necessary for dependable flow in both mass-flow and funnel-flow bins. These dimensions have been calculated on the basis of the solid's frictional and cohesive properties. In all cases, it is assumed that flow occurs only under the action of gravity, i.e., without internal or external assistance.

Generally, these dimensions are a function of the time the solid remains in storage at rest, moisture content, temperature, size consist, and the overpressure, if any, applied to it during storage. The P-FACTORs are the ratios of applied compaction pressure to the pressure resulting only from gravity flow. If there are no overpressures, the critical dimensions for P-FACTOR = 1.0 should be used. If the P-FACTOR is greater than one, it is assumed that overpressures have been exerted on the solid during storage but are removed when the solid must flow.

Mass-flow bins have hopper walls which are smooth and steep enough to allow flow; hence, stable channels within the material (ratholes) do not develop. Only two dimensions, both of which are shown in Figure 1B1, are specified: BC, the minimum outlet diameter for a conical hopper, and BP, the minimum width for a slotted or oval outlet. The length of the slot or oval should be at least three times its width.

A funnel-flow bin is created whenever the hopper walls are not steep and smooth enough to allow flow. Slotted outlets are recommended for these bins unless the material flows freely. To prevent stable arches from flowing, the width of the slot must be at least equal to BF. In a funnel-flow bin, the solid is held up at the walls and flows only within a circular channel whose diameter is approximately equal to the diameter or length of the effective outlet. If this flow channel diameter is less than the critical rathole diameter DF, a stable rathole is likely to form, and the live capacity of the bin will be essentially only that material which is in the flow channel above the outlet. To prevent

stable ratholes from forming, funnel-flow bins should be designed with slotted outlets whose length is at least as large as DF.

Generally, DF is proportional to the consolidating pressure imposed on the solid during filling of the bin. Hence, in the upper regions of a bin where pressures are low, the critical rathole diameter DF is small, and the flow channel diameter may exceed DF. This causes the rathole to be unstable at this point, allowing the material to collapse into the stable rathole below. A partial emptying of the bin will result.

Calculation of Effective Head (EH). The critical rathole diameter, DF, is a function of the major consolidating pressure which acts on the solid in the bin. It is convenient to express this pressure in terms of EH, the effective consolidating head of solid in the bin, as follows:

$$EH = [R/(\mu k)] [1 - EXP(-\mu k\, H/R)]$$
or $\qquad$ [Eq 1B2]
$$EH = 2R,$$

whichever is larger. The parameters are:

R = hydraulic radius of the cylindrical portion of the bin, i.e., the ratio of the cross-sectional area to the circumference

R = D/4 for a circular cylinder of diameter D or a square cylinder of side D

R = W/2 for a long rectangular cylinder of width W

μ = tan (PHI-PRIME), coefficient of friction between the stored solid and the cylinder walls (see Section III)

k = ratio of horizontal to vertical pressures; a value of 0.4 is usually acceptable within the cylinders

H = height of the cylindrical portion of a bin.

Calculation of P-FACTORs. The magnitude of the over-pressure factor can be estimated for vibration, impact during charging into the bin, external loading, and fluid (gas) flow loading as follows:

Vibration: P-FACTOR = a_y/g
or $\qquad$ [Eq 1B3]
$$(1 + a_x/g),$$
whichever is larger, where:

a_x = vertical upward component of acceleration imposed on the solid

a_y = horizontal component of acceleration imposed on the solid

g = gravitational acceleration constant.

Impact Pressure From Fall Into a Bin: A coarse material compacts as it is charged into a bin under the impact of the falling particles. When the material contains fines and the impact area is close to the outlet, the impact P-FACTOR should be used in the design.

$$\text{P-FACTOR} = (1 + m) [w/(A\,B\,GAMMA)] \sqrt{2h/g} \qquad [Eq\ 1B4]$$

where:

w = weight flow rate into the bin

h = height of fall

m = 0 for a long rectangular outlet

m = 1 for a circular or square outlet

A = area impacted by the falling stream of solids

B = outlet size or bin dimension in the region of impact, i.e., the diameter in a conical hopper, or the width in a wedge-shaped or transition hopper

GAMMA = bulk density of solid.

External Loading: If the solid has been compacted by an external load, F, such as the weight of a tractor passing over an outside stockpile, the overpressure factor at the point of application is given by:

$$\text{P-FACTOR} = (1 + m)\, F/(A\,B\,GAMMA) \qquad [Eq\ 1B5]$$

where:

A = area of load application.

Liquid or Gas Flow Loading: If the solid has been subjected during storage to fluid or gas flow, e.g., by an air blaster or draining of a saturated solid, or the flow of air or gas during drying or chemical processing, the overpressure factor is given by:

$$\text{P-FACTOR} = 1 + (dp/dx)/(GAMMA) \qquad [Eq\ 1B6]$$

where:

dp/dx = the downward (vertical) fluid or gas pressure gradient at the bin outlet.

In any of the above cases, if the overpressure continues to act during the discharge of the solid and is

positive downward, the overpressure factor need not be applied. If the downward pressure acts *only* during discharge, the dimensions given in Section I for P-FACTOR = 1.0 may be reduced by dividing them by the appropriate P-FACTOR.

When considering the effect of overpressure which acts on a solid during time of storage at rest, it is not necessary that the overpressure act during the entire time at rest. Soon after overpressure has been applied, a solid reaches the maximum densification associated with that overpressure. Hence, the critical outlet dimensions will be essentially the same, whether the overpressure acts for a short time or continuously during the entire time at rest.

Limits on Bin Sizes. The bin dimensions in Tables B1 and B2 apply to bins of unlimited maximum size. Some materials will compact in large bins, causing large stable arches in the upper part of the hopper, while the lower portion may discharge without a problem, which can lead to a very dangerous condition. When a large arch is broken high in the hopper, the impulse of the falling material may cause structural damage to the bin and possibly tear the hopper from the vertical bin section.

Often, the upper limits on bin size occur only for compaction with time or for significant overpressure conditions. If this is the case, the bin can be designed for an unlimited size, provided the critical time and overpressure effects are not exceeded during the bin operation.

Section II — Bulk Density

The bulk density, GAMMA, of a material is used in bin load and capacity calculations. Values of bulk density of the sample tested are given in this section as a function of the effective head of solid EH and the major principal consolidating pressure SIGMA1. The relationship is:

$$SIGMA1 = EH \times GAMMA \qquad \text{[Eq 1B7]}$$

Within the cylindrical part of a bin, the effective consolidating head is given by Eq 1B2. At the outlet of a mass-flow bin, the head is given by Eq 1B1.

Bulk density values have been computed from measured compressibility parameters of the material. Generally, all materials have a minimum density, GAMMA MINIMUM, without fluidization. The relationship between bulk density and consolidating pressure applies to densities greater than GAMMA MINIMUM.

Section III — Maximum Hopper Angles for Mass Flow

A solid sliding on a bin wall encounters frictional resistance proportional to the wall friction angle PHI-PRIME. This angle generally depends not only on the roughness of the wall but also on the pressure which the solid exerts on the wall. For hard wall surfaces, the friction angle decreases as the solids contact pressure increases. This pressure, which varies with position in the bin, is usually smallest at the outlet.

THETA-C and THETA-P are the recommended maximum hopper slope angles, measured from the vertical, for conical and transition mass-flow hoppers, respectively (see Figure 1B1). These values have been calculated from the friction tests (wall yield loci) and are tabulated for a series of widths of oval hoppers and diameters of conical hoppers. To minimize headroom, consider changing the slope of the hopper wall as a function of position. For example, if a conical hopper is to be designed with an outlet diameter of 1 ft and the recommended THETA-C is 14° at a 1-ft diameter and 23° at 2-ft and larger diameters, use two cone sections. In the lower section, where the diameter varies from 1 ft to 2 ft, use a hopper angle of 14°. Above the 2-ft diameter, use a hopper angle of 23°.

Often, both continuous flow and time friction tests are run on a material. If the solid adheres to the wall with time, the time test results will indicate an increase in friction angles. To overcome this time effect, the hopper walls should be made steeper, or other means, such as vibration of the bin walls, should be provided to start flow.

Section IV — Critical Solids Flow Rate

The maximum rate, Q, at which a coarse solid (say, 95 percent plus ¼ in.) flows out of a mass flow hopper is practically independent of the head of solid and is given approximately by

$$\text{[Eq 1B8]}$$

$$Q = (A\ GAMMA)\ \sqrt{B\ g/[2(1\ +\ m)\tan\ (THETA)]}$$

where:

A = area of the outlet

B = diameter or width of the outlet

THETA = THETA-P for rectangular or oval outlets,
or
THETA-C for circular outlets.

Predicting the flow rate of fine solids is more complicated because their outflow rate is critically affected by the amount of air entrained in the solid. If that amount is large, the solid may flush out and flow uncontrollably. If the solid is deaerated, the flow rate is much smaller. The amount of air entrained with the solid depends on the rate of charge per unit area, i.e., on the linear velocity of deposition of the solid. The higher the velocity, the more air is entrained. A stream of solids distributed over the top area of a bin entrains less air than a concentrated stream, which impacts a small area and often buries itself and the entrained air within the mass.

As the mass of solid flows down the cylinder while additional solid is charged into the bin, the head of solid causes an increase in solid pressure. This densifies the solid, decreases the pore size, and increases the air pressure. During periods of storage without charge or with low charge rates, air escapes from the bin, and air pressure drops. A prolonged period without charge produces equalization of air pressure and deaeration of the solid.

As solid flows in the hopper toward the bin outlet, solid pressure decreases, the solid expands, and air pore pressure drops. If sufficient air escapes from the bin, the pressure drops below ambient, causing air counterflow at the outlet, which hinders the outflow of the solid.

In the usual operation, the function of a bin is to provide surge capacity. The charge rate fluctuates between zero and a maximum value. The discharge rate may fluctuate similarly. The design should provide for the full range of the specified conditions. The critical flow rate (discussed previously) is the maximum flow rate at which reliable flow of the solid can be expected under the worst condition, specifically, after prolonged storage at rest.

The rate is tabulated as a function of effective head of solid in the bin. It is computed on the assumption that there is no air in-flow or out-flow along the height of the bin, that air pressure at the outlet of the bin is the same as at the top of the bin, and that the feeder outlet is not sealed against air in-flow. Should the operating conditions deviate from these assumptions, a controlled rate different from the critical may be obtained. If the tabulated flow rates are smaller than desired, the possibility of using an air permeation system can be considered.

If the specified flow rate from a bin is close to the critical values, it is particularly important that the feeder withdraw uniformly across the entire outlet. If this is not done, localized limiting rate effects may occur at the outlet, especially at the ends of a slotted outlet. This may result in pulsating flow from the bin, the development of fast-flowing columns, and an uncontrolled rate of withdrawal with flushing.

All the above comments also apply when a gas other than air is used in the bin. The critical property is the viscosity of the gas. The permeability tests discussed here were done with air at room temperature. When the gas or temperature are different, the coefficient or permeability must be modified, as discussed below.

Section V—Air Permeability Test Results

Values of air permeability are expressed as a function of the bulk density of the solid. These values are used to calculate the critical flow rates, (see Section IV) and to design air permeation systems.

The test method is based on the assumption of laminar flow of gas. This assumption is generally valid for all powders and for most materials which have a significant portion of particles less than 20 mesh in size.

The permeability factor, K, has the dimension of velocity and is inversely proportional to the viscosity of the gas. The results can be adjusted to elevated temperatures and to other gases by multiplying the constant, KO, by the ratio of the viscosity of air at room temperature to the gas for the temperature in question.

GLOSSARY OF TERMS AND SYMBOLS

Arching	a no-flow condition in which material forms a stable arch (dome, bridge) across the bin
Bin	container for bulk solids with one or more outlets for withdrawal of solids either by gravity alone or by gravity assisted by flow-promoting devices
Cylinder	vertical part of a bin
Expanded flow	flow pattern which is a combination of mass flow and funnel flow
Feeder	device for controlling the rate of withdrawal of bulk solid from a bin
Flow channel	space in a bin through which a bulk solid is actually flowing during withdrawal
Funnel flow	flow pattern in which solid flows in a channel formed within stagnant material
Hopper	converging part of a bin
Mass flow	flow pattern in which all solid in a bin is in motion whenever any of it is withdrawn
Piping	a no-flow condition in which material forms a stable vertical hole within the bin
P-FACTOR	the ratio of the applied solids compacting pressure to the solids pressure during steady gravity flow.
Ratholing	same as piping
A	area of impact of falling stream of solids, sq ft
a_x, a_y	vertical and horizontal accelerations, respectively, ft/sec^2
B	span across a bin at any elevation of the bin, ft

BC	minimum diameter of a circular outlet in a mass-flow bin, ft
BF	minimum width of a rectangular outlet in a funnel-flow bin, ft
BP	minimum width of an oval outlet in a mass-flow bin to prevent arching, ft
D	diameter of cylindrical portion of a bin, ft
DF	critical piping (ratholing) dimension, ft
EH	effective consolidating head, ft
F	force from an external load on material, lb
f_c	unconfined compressive strength of a solid, psf
g	gravitational constant = 32.2 ft/sec^2
H	height of cylinder, ft
h	height of fall of material, ft
K	permeability factor, ft/sec
k	ratio of horizontal to vertical pressure
KO	permeability constant, ft/sec
L	length of hopper outlet, ft
m	parameter equals 0 for rectangular outlet and 1 for circular or square outlet
p	liquid or gas pressure, psf
Q	maximum discharge rate of a coarse solid, lb/sec
R	hydraulic radius, ft
S	shearing force applied to a shear cell, lb
V	normal force applied to a shear cell, lb

W	width of rectangular bin cylinder, ft	θ_p, THETA-P	maximum recommended angle (from vertical) of side walls of transition hoppers for mass flow, degrees
w	weight flow rate into the bin, lb/sec		
x	vertical coordinate, ft	μ, MU	tan (PHI-PRIME)
y	horizontal coordinate, ft	σ, SIGMA	normal stress applied to a shear cell, psf
γ, GAMMA	bulk density, pcf		
δ, DELTA	effective angle of internal friction of a solid during flow, degrees	σ_1, SIGMA1	major consolidating pressure, psf
		τ, TAU	shearing stressing applied to a shear cell, psf
θ_c, THETA-C	maximum recommended angle (from vertical) of conical hoppers and end walls of transition hoppers for mass flow, degrees	ϕ', PHI-PRIME	kinematic angle of friction between a solid and a wall, degrees
		ϕ_t, PHI	angle of internal friction of a solid in incipient flow, degrees

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